2018

The Sidewalk Problem: An examination of the avoidance behaviours employed during a head-on collision course with an approaching person

Lana M. Pfaff
Wilfrid Laurier University, pfaf1880@mylaurier.ca

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By

Lana M. Pfaff

THESIS

Submitted to the Department of Kinesiology and Physical Education

in partial fulfillment of the requirements for

Master of Kinesiology

Wilfrid Laurier University

Acknowledgments

I would like to take this opportunity to thank the many people who contributed to this thesis and my time at Laurier.

To my committee members, Dr. Jayne Kalmar and Dr. Stephen Perry: It has been a pleasure to work with you and be taught by individuals so passionate about learning and research. Thank you for your valuable advice and suggestions throughout this project.

My LPMB lab: From the moment I started as an RA four years ago, I have been surrounded by individuals who pushed me to reach my greatest potential. Thank you for creating a space full of laughter, friendship, snacks, and collaboration. Jessie, this thesis would not have been possible without you. Thank you for your countless hours, Oscar- worthy acting, and your bright smile. Jaime and Alyssa, thank you for being there through my deepest lows and highest highs. With you two, I have eaten more candy in the last two years than my entire childhood, driven more miles, and laughed until my stomach hurt and I wouldn't have wanted to do it with anyone else.

Dr. Mike Cinelli: My supervisor, mentor, and friend. Words cannot begin to describe how thankful I am to have worked with you these last six years. Thank you for the countless hours of discussing research and new ideas, for calming me down in times of momentary panic, for your 2 AM emails, your patience, your commitment, and your advice. You have pushed me to excel in not only my academic endeavors but everything else I have tackled during these past six years. Even though you still make us Optofix all of our data and are forever referring to BPG (which in case you forgot, I didn't take), I cannot thank you enough for all you have done for me. Your ability to instill confidence and excite others about learning is something I hope to emulate in my future as a teacher.

To my friends and family: Thank you for being my biggest supporters, I would not be where I am today without your love and friendship. Especially, my mom, dad, and sister, thank you for always reminding me I am more than capable of anything I set my mind to. Thank you for always giving me a reason to smile, and for showing me love beyond any measure. Alex, thank you for being my rock and for endlessly listening to all of my presentations. Jenn, thank you for being the best friend a cousin could ask for. Thank you for all of your surprise Starbucks deliveries, the much needed trips to the mall, and for always being there when I needed you most.

Finally, I would like to dedicate my thesis to my grandmother. A few weeks into beginning this degree, we lost my Nana. I cannot begin to express my deepest gratitude for the friends, family, and colleagues who supported me through that time. I am forever thankful for my Nana's support and the time we had together, during which she showed me the importance of creating a life full of love and family. Nana, I miss hearing you call "hello" from the other room when I came in the front door, your chocolate chip cookies, and your sly laugh after an unexpected joke. I am so lucky to have had you in my life. I love you and miss you.

Abstract

Individuals use visual information in order to guide their avoidance behaviours. More specifically, individuals may directly perceive the time prior to colliding with an approaching obstacle (i.e., time to contact, TTC) in order to determine when to avoid. However, if the path of the approaching obstacle is highly predictable, individuals do not use a consistent TTC (Cinelli & Patla, 2007). Additionally, individuals use body- and action-scaled information to control their movements (Fajen, 2013). These avoidance behaviours differ when avoiding a human obstacle compared to an inanimate object (Hackney, Cinelli, & Frank, 2015; Knowles, Kreuser, Haas, Hyde, & Schuchart, 1976). As such, the purpose of this thesis was to examine the avoidance behaviours of individuals during a head-on collision course with an approaching person. This task assessed steering strategies in a confined environment while individuals avoided an approaching person who walked along one of four randomized paths. Avoidance behaviours were compared between males and females (Study 1), and female rugby players versus female non-athletes (Study 2) to assess the potential differences in the use of body-scaled and action-scaled information during the same paradigm. Specifically, the objectives of the current thesis aimed to examine (1) how young adults control their actions and (2) the effects of sport-specific training on avoidance behaviours of rugby players during a collision course with an approaching person. Young adults (N=20, $\bar{x}$= 22.25 ± 1.5 years, 10 males) and female rugby players (N=10, $\bar{x}$= 20 ± 0.94 years) were instructed to walk along a 10m path towards a goal located along the midline. A female confederate positioned initially along the midline 180° from the participant walked towards the participants to one of four predetermined final positions: 1) along the midline in the participants' starting position; 2) stopped along the midline 2.5 m from her starting position; 3) to the left of the participants' starting position; and 4) to the right of the participants'

starting position. Results from both studies revealed that when the path of the confederate was uncertain, individuals used a consistent TTC to determine when to change their path. TTC described the temporal distance between the confederate and the participant at the point of a change in path of the participant. TTC was found to be affected by sex and sports specific training, such that males avoided significantly earlier (i.e. larger TTC) and rugby players avoided significantly later (i.e. smaller TTC) than non-athlete females. However, following a change in path, sex and sport-specific training did not impact the avoidance behaviours of the groups, but rather the environment was the regulating factor. Avoidance strategies differed when the confederate stopped 2.5 m from her starting position from the other path conditions. When avoiding the stopped confederate, individuals avoided earlier (i.e. larger TTC), at a slower rate, and to a lesser magnitude. This suggests individuals may have selected their strategies based on comfort. More specifically, when the confederate stopped 2.5 m from her starting position, the decrease in uncertainty of her movement may have allowed for more comfortable, self-paced avoidance. However, during the conditions in which the confederate's path was highly uncertain, individuals did not use a single avoidance strategy, instead their behaviours were based on the relationship between the environment and the observer (i.e. sex and sport-specific training).

Table of Contents

Table of Figures and Tables

Table List

Figure List

Glossary of Terms and Abbreviations

ML: Medial-Lateral, reference to anatomical direction

AP: Anterior – Posterior, reference to anatomical direction

COM: **Centre of Mass,** weighted average of the whole body mass (Winter, 1995). Within the current study, COM was calculated using a weighted average of the medial-lateral and anterior-posterior coordinates of the digitized points on the left and right shoulders, the anterior superior iliac spine of the participant, and the posterior superior iliac spine of the confederate.

TTC: Time to Contact, the temporal proximity prior to contacting an object (Lee, 1976).

Chapter 1

General Introduction

1.1 Sensory Control of Locomotion

People are required to avoid colliding with other people and environmental obstacles every day in order to navigate the world. To successfully complete this task, individuals must accurately identify and integrate information from their sensory systems. Three major sensory systems are involved in balance control and locomotion, and each play a specific role (Winter, 1995). The vestibular system provides information regarding the position and movement of the head with respect to linear and angular accelerations (Winter, 1995). This information is important in orientation and localization of one's head in space (Ivanenko, Grasso, Israël, & Berthoz, 1997). The somatosensory system provides proprioceptive information which may describe the position and the velocity of all body segments and their contact with external objects (i.e. the ground) (Winter, 1995). Finally, the visual system provides information about what is present in the environment. The visual system is the only sensory system that can provide information about the environment at a distance. Whereas both the vestibular and somatosensory systems are important in reactive control, the visual system allows for the anticipatory control of movement prior to reaching a potential perturbation (Patla, 1997). As such, the visual system is critical in the successful navigation of complex and dynamic environments.

During locomotion, the visual system provides an abundance of instantaneous information about the environment, self-motion, and an individual's body with respect to their surroundings (Patla, 1998). The visual system can be used in a feed-forward manner, to guide anticipatory actions. Previous research has demonstrated the relationship between vision and locomotion in order to control movements across environmental conditions and safely steer to open spaces (Cinelli, Patla, & Allard, 2009; Hollands, Marple-Horvat, Henkes, & Rowan, 1995; Hollands, Patla, & Vickers, 2002; Patla & Vickers, 2003), and therefore, for the purpose of this thesis, the primary focus will rest on the visual system and its sensory contribution to locomotion and obstacle avoidance.

1.1.1. The Visual System

The visual system receives stimulations from the optic array, which is projected onto the retina to form an image (Tresilian, 2012). A concept first proposed by Gibson (1979), optic array is defined as the "spatial pattern of light reaching a particular point of observation from its surroundings" (Tresilian, 2012, pg. 197). The lenses of the eye project and focus the optic array onto the retina. The retina is the light sensitive layer at the back of one's eye, and the beginning of visual processing (Snowden, Thompson & Troscianko, 2006).

The retina is comprised of five layers made up of neurons and photoreceptors, which upon stimulation from light, will initiate neural processing. There are two types of photoreceptors in the eye; cones and rods. Cones are responsible for detailed colour vision, whereas rods are sensitive to light and motion. The distribution of photoreceptors across the retina is not uniform as cones are heavily centralized to the fovea, whereas rods are more present within the periphery. This distribution of photoreceptors has a functional impact on visual acuity which will be discussed later. The photoreceptors synapse with horizontal and bipolar cells, then retinal ganglion cells, which project towards the brain through the optic nerve (Snowden et al., 2006; Tresilian, 2012). The optic nerve from each eye converges at the optic chiasm. At this point, axons from the left half of each eye form the left optic tract, and axons from the right form the right optic tract. The optic tract projects to the lateral geniculate nucleus (LGN). The lateral geniculate nucleus, within the thalamus, acts as the relay centre from the optic tract to the occipital lobe (Snowden et al., 2006). From the LGN, the genuculostraite pathway continues to the primary visual area (V1) in the cortex. V1 is retintopically mapped, as such, provides an ordered map of the visual world. More sensitive regions of the retina (i.e. the fovea) are associated with larger regions on the cortex (Tresilian, 2012). As such, one's central field of view is emphasized within visual processing.

Beyond V1, more than 30 visual areas exist and are responsible for higher processing (Snowden et al., 2006). Two primary streams have been suggested to guide the transfer of visual information from V1 to extrastriate areas (Milner & Goodale, 1995). The ventral stream projects from area V1 to the inferotemporal cortex and sends information related to vision-for-perception (Tresilian, 2012). This information is used to make conscious decisions and planning goal-specific action. The dorsal stream, from area V1 to the parietal lobe, provides information for vision-for-action (Milner & Goodale, 1995; Tresilian, 2012). This stream mediates the control of online visual control of action. In addition to information from area V1, the dorsal stream also receives input from the superior colliculus (Goodale, 1993). The superior colliculus is involved in saccadic eyes movements (Sparks & Mays, 1990), as well as the coordination of eye, head and postural movements (Martin, Jessel, Kandel, & Scwartz, 1991). As such, the relationship between the dorsal stream and visuomotor control is clear.

When motion is present (either self-simulated or within the environment), the point of observation changes, resulting in optic flow. These changes in light intensity represent features within the environment and produce a moving image on the retina. This image flow is comprised of both a translational component (translation of the eye through its surroundings) and a rotational component (rotation of the eye within the socket). Together, perception of self-motion is available. This information is processed beyond the primary visual cortex, in area V5. Area V5 is critical in processing the dynamic aspects of visual information (Snowden at al., 2006). Researchers have indicated a high level of sensitivity to this component of their visual surrounding. To test this sensitivity, Lee and Lishman (1975) examined the effects of a “moving room” on postural sway. The room was composed of fixed floors with moveable walls. It was found that when the walls moved (optic flow information was provided); postural sway was induced in participants. Moreover, the direction of the sway was not random but rather in the direction of wall movement (Lee & Lishman, 1975). As such, visual information, such as optic flow, is available to individuals from the environment and may drive behaviour.

Not only is pertinent information readily available in the environment, but individuals are capable of processing this information in order to make appropriate decisions related to their movements. This process is complex and occurs within numerous parts of the brain, all of which play specific roles in the successful perception of one’s environment.

1.2 Perception and Action Integration

It is clear the visual system provides an abundance of information from the optical array. The continuous availability of information by the visual system is a critical component of the manner in which an individual determines the appropriate action to employ under particular circumstances. In 1979, Gibson proposed the idea that individuals may use the information from their sensory systems directly to drive action as opposed to being internally-represented and mediated. This revolutionary theory illustrates the dynamic relationship between the environment and the individual within it.

More specifically, Gibson proposed that goal-oriented locomotion is guided by visual perception. He suggested that "we must perceive in order to move, but we must also move in order to perceive" (Gibson, 1979, pg 223). As such, in order to acquire adequate information about the environment, we must move our point of observation. This is the driving concept behind the theory of perception and action integration. This cyclic relationship suggests that precise sensory perception will guide actions, which will in turn update perception and direct subsequent movement. As such, perception and action are tightly coupled and dependent on one another. The relationship suggests that the performer and the environment act as a system, in which changes to one will have a direct effect on the other.

This framework contributes to successful navigation through a cluttered environment on a daily basis; however, it requires the ability to both accurately perceive the environment and the opportunity for action within it. These opportunities for action presented by the environment are called *affordances* (Gibson, 1979). Based on the Theory of Affordances, an environment or environmental object may be considered with respect to the actions they allow. As illustrated by Fajen, Riley, and Turvey (2008) there are six key features of affordances; affordances are 1) real; 2) observer-specific; 3) illustrate the reciprocity of perception and action; 4) allow for prospective control of behaviour; 5) are meaningful; and 6) are dynamic (Fajen, Riley, & Turvey, 2008). These components contribute to an individual's ability to directly perceive their surroundings and successfully make decisions on the appropriate action to take. As emphasized in the theory of direct perception, affordances are consistently and directly available from information in the optic array, and are not stored as a memorial representation (Gibson, 1979).

With this information, an individual will use a unique frame of reference to direct action in relation to the presented environment. As such, in accordance with the key features of affordances, possibilities for action are determined based on the fit between the environment, the individual's body size (body-scaled), and their action capabilities (action-scaled). Body-scaled affordances suggest that the environment can be normalized to an individual's body size, and their actions are determined based on a ratio between the individual's body size and dimensions of the environment (Warren & Whang, 1987). The passability of a gap has been widely used to display body-scaled affordances, as young adults will change their behaviours while passing through an aperture if the dimensions are less than 1.3x an individual's shoulder width (Hackney & Cinelli, 2013; Hackney, Vallis, & Cinelli, 2013; Warren & Whang, 1987).

Furthermore, affordances may be perceived based on action-scaled information, or rather an individual's abilities with respect to the environment. For example, the "catchableness" of a ball depends on how fast an individual may get to the point prior to the ball hitting the ground (i.e. stride length) (Fajen, Riley, & Turvey, 2009; Warren, 2007). As such, changes to both the environment (i.e. obstacle characteristics) and the observer (i.e. abilities) will impact behaviour. Throughout this thesis we will revisit the effects of changes to both components and their resulting influence on an individual's behaviour.

1.3 Vision for Steering

Multiple sensory systems are required for controlling posture and locomotion; however, information about body posture and movement from the visual system is given higher priority over information provided by the other sensory systems (Patla, 1997). A variety of information can be extracted from the visual system in order to move safely through the environment. Exteroceptive information (information regarding one's position/movement relative to objects within the environment) is used in a feed forward manner, in which it may be used to proactively control movement. The interpretation of this exteroceptive information is affected by an individual's past experiences. Consequently, visually observable and visually inferred characteristics of the environment will affect how an individual avoids an obstacle (Patla, 1997). In addition to feed forward control, visual information is also used in an online mode. Exproprioceptive information (information about one's position/movement in space) is acquired through optic flow, and can provide information about self-motion (Patla, 1997). Prior to reaching the site of a potential perturbation, there are a number of avoidance strategies that may be initiated. These strategies include actions such as: 1) alternative foot placements by modulating step width and/or length, 2) increase ground clearance when stepping over an obstacle or increasing head clearance when avoiding an obstacle above ground, 3) stopping locomotion all together, and 4) changing direction of locomotion (steering). These strategies rely heavily on vision (Higuchi, 2013).

Previous research suggests that during locomotion, individuals will fixate ahead at their goal, in far space, towards the direction in which they are moving (Cinelli et al., 2009; Higuchi, 2013). However, during obstacle avoidance this strategy seems to be broken up into two components. In a study conducted by Patla and Vickers (2003), gaze analysis suggested that during the approach phase, individuals fixate on the obstacle (fixation on object of interest). This obstacle fixation takes place up until the point of crossing the obstacle, in which gaze will then shift to the goal (Patla & Vickers, 1997). These fixations take place in addition to travel fixation to provide information about the environment and potential constraints. Furthermore, individuals fixate approximately two steps (800 -1000ms) ahead of their current position (Patla & Vickers, 2003). This use of information allows for sufficient time to modify behaviours if necessary. As such, gaze behaviours are not conducted randomly, but rather are based on strategies related to one's goal.

Following the detection of an obstacle, determining when to initiate an avoidance strategy is also dependent on visual information. Temporal information plays a vital role in the use of vision to control actions. More specifically, the ability to determine the temporal proximity prior to contacting an object, known as Time-to-Contact (TTC) is used during interceptive and avoidance tasks (Lee, 1976). TTC is specified as the inverse rate of dilation of the retinal image of the approaching object, and is represented by the optical variable (tau) (Lee, 1976). As such, tau is equal to the size of the image on the retina, divided by the rate at which the image is expanding. Tau can be directly perceived without information about the object's distance and approach speed, but rather information about optic flow. It is suggested that individuals will initiate an avoidance strategy when the approaching obstacle is a "safe" distance away. The faster an object is approaching, the greater the safe distance (Lee, 1976). Three cases of TTC have been examined within research (Tresilian, 1991). The first case is one in which the observer is moving and the object is stationary, like a person walking towards a tree. The second is the opposite, in which the observer is stationary and the object is moving towards them, such as a pitch being thrown at a catcher in baseball. The last scenario involves both the observer and the object moving towards one another. This situation is commonly observed in sport contexts, or when two people are walking towards each other on a sidewalk.

TTC information is often used during interceptive tasks. Interceptive tasks involve initiating an appropriate action at a precise time so as to make contact with the object of interest. For example, an outfielder in baseball will utilize an interceptive behaviour to catch a fly ball. Research has been examining the use of visual regulation of interceptive action for some time now. Lee, Lishman, and Thompson (1982) examined the concept with respect to long jumpers and their action strategy while approaching the take-off board. It was found that athletes have little variability in their stride length until a few steps prior to the take-off board. Stride length variability increased as the runners approached the board, whereas the variability in footfall positions decreased. It was concluded that the change in variability was indicative of a zeroing-in phase of the jumper's approach. This phase was suggested to be visually driven through use of TTC information. TTC information was obtained through the rate of expansion of the board on the retina to modulate their foot placement during approach (Lee, Lishman, & Thomson, 1982). TTC information is also used when the object of interest is moving. A study conducted by Savelsburgh, Whiting, Burden, and Bartlett (1992) examined the onset of muscular activity in the hand in response to approaching tennis balls. The tennis balls moved towards the participants at three different speeds while changing their size during the approach. Results revealed the onset of muscle activation was not significantly different across velocities, rather the movement was initiated at a constant time from contact (Savelsbergh, Whiting, Burden, & Bartlett, 1992). As such, it was suggested that participants used TTC information to activate the onset of muscle at a particular threshold (tau margin). These studies suggest TTC information is readily available within the environment, and is used extensively to determine the appropriate time to initiation a movement in order to successfully intercept an object.

TTC information has also been demonstrated to be used during tasks involving whole body movement. Lee and Reddish (1981) found that visual expansion of a stationary object guides whole body movements of gannets. While diving into the water, it was found that the birds would consistently retract their wings at a particular optical expansion threshold (Lee & Reddish, 1981). Although the findings from this study are highly controversial, a large body of literature suggests that visual information about potential time to contact may be used to determine when an individual should initiate an avoidance or interceptive strategy (Cinelli & Patla, 2007; Huber et al., 2014; Peper, Bootsma, Mestre, & Bakker, 1994; Savelsbergh et al., 1992; Watson et al., 2011). This change in action is guided by an optical expansion threshold.

1.4 Objectives of the Thesis

It is understood that individuals use visual information in an online manner to plan and adapt movements to dynamically changing environments. This visual input provides the individual with information related to the environment, as well as their body relative to that environment. Individuals are also able to use this information to accurately determine when and where they may come in contact with an object. More specifically, individuals are well adept at determining the time prior to contacting an object, known as time-to-contact (TTC). Once an individual has detected a potential collision, they may use temporal visual information to guide their future movements. Research has long sought to identify how individuals use TTC to drive their avoidance behaviours. Previous literature has examined obstacle avoidance strategies in a number of contexts, including the use of virtual reality, stationary obstacles, moving inanimate obstacles, and human obstacles. Until now, the paradigms in past research used obstacles that move along highly predictable paths, which are not realistic to everyday life and may not present a true understanding of obstacle avoidance strategies. The objective of the first study was to investigate the avoidance strategies of young adults during a head-on collision course with an approaching person. The path of the confederate was unknown to the participants throughout the experiment, and therefore this thesis may provide a greater insight into how individuals use TTC information to guide their behaviours when avoiding other people in everyday life.

Individuals who train at an elite level practice their ability to avoid obstacles and fit between gaps on a regular basis. It is understood that athletes with this sport-specific training may have better perception for action skills through a perceptual attunement to information variables directly related to their success (Fajen et al., 2008). Nevertheless, in the events of a collision during a game or practice, consequences including a negative impact on one's performance as well as injury may occur. The research related to the effects of sport-specific training on obstacle avoidance is highly controversial and suggests the quantifiable differences in their behaviours compared to non-athletes is highly context specific (Baker, 2015; Higuchi et al., 2011; Pfaff & Cinelli, 2017). Additionally, previous research investigated the avoidance behaviours of athletes with stationary obstacles; however, athletes compete in dynamically changing environments in which they must interact with opposing players. The objective of the second study was to investigate the effects of sport-specific training on the avoidance behaviours of rugby players during a head-on collision course with an approaching person. The current thesis may provide further information into the perception-action strategies of athletes who are specifically trained to avoid moving obstacles, revealing the effects of their sport-specific training.

In combination, the current thesis set forth to identify what information is guiding an individual's avoidance behaviours of an approaching person. In addition, this thesis aimed to investigate what factors individuals are controlling throughout their avoidance in order to be successful, and how these factors change based on the individual's characteristics (i.e., body size and capabilities) and the environment.

Chapter 2

Avoidance behaviours of young adults during a head-on collision course with an approaching person

2.1 Introduction

People navigate cluttered environments with relative ease on a daily basis. Whether it is through a doorway, in a busy shopping centre or passing another individual on the sidewalk, people are required to integrate a multitude of information from their sensory systems to successfully walk through the world. During locomotion, the visual system provides an abundance of instantaneous information about the environment, self-motion, and an individual's position with respect to their surroundings (Patla, 1998). The visual system can be used in a feed-forward manner to guide movement. Previous research has demonstrated the vital relationship between vision and locomotion in order to adapt movements to environmental conditions and safely steer to open spaces (Cinelli, Patla, & Allard, 2009; Hollands, Marple-Horvat, Henkes, & Rowan, 1995; Hollands, Patla, & Vickers, 2002; Patla & Vickers, 2003). The ability to perceive motion of an approaching object and make appropriate adjustments to the behaviours required to avoid a collision is critical to safe locomotion in a dynamically changing environment. Specifically, in order to initiate movements at the appropriate time, individuals use temporal information to estimate time to contact (TTC) (Cinelli & Patla, 2007; Lee et al., 1982; Savelsbergh et al., 1992). After determining when to initiate a movement, how one successfully moves through their environment is dependent on a number of factors. These factors include characteristics of the individual (body and action capabilities) and the physical properties of the environment, which determine the opportunities for action available to the individual (affordances) (Gibson, 1979).

One of the ways in which people successfully avoid obstacles is maintaining personal space. Personal space has long been examined with respect to maintaining a comfortable distance from another person during social interactions (Sommer, 1959). However, during avoidance situations, personal space is defined as the protective zone an individual maintains while walking (Templer, 1992). The protective zone is maintained to allow for time to perceive, evaluate, and react to potential hazards in the environment. Gérin-Lajoie and colleagues (2005) examined the maintenance of protective zone across environmental conditions. Their findings revealed that participants maintained an elliptical shaped protective zone of 2.11m anteriorly and 0.48m medial-laterally when avoiding a stationary obstacle. This protective zone decreased by 22% when the obstacle was moving, suggesting participants took more time to gather information related to the obstacle prior to initiating their avoidance (Gérin-Lajoie, Richards, & McFadyen, 2005).

Although the previous research examined obstacle avoidance with moving objects, there is a clear lack of research which addresses human obstacle avoidance. Humans are social beings and interact with other people on a daily basis, therefore it is critical to understand how behaviours differ when avoiding another person compared to an inanimate object (whether stationary or moving). Knowles and colleagues (1976) examined the difference in personal space around an empty bench or a bench occupied by a single person or multiple people. It was found that individuals will employ a wider path trajectory around the bench occupied by a person compared to the empty bench, and trajectories increased with the number of people occupying the bench (Knowles et al., 1976). These findings suggest that individuals will increase their protective zone to accommodate for the possibility of movements from other people.

The current study aimed to identify the avoidance strategies of young adults during a head-on (180^{o}) collision course with an approaching person. Previous research has suggested individuals use TTC information in order to determine when to avoid an approaching person. In order to test whether individuals attempt to maintain a consistent TTC value when avoiding an approaching object, Cinelli & Patla (2007) had an object moving at a constant rate (i.e. not accelerating) toward a participant. The path of the object was highly predictable and therefore individuals did not maintain a consistent TTC when producing a change pathway (Cinelli & Patla, 2007). The current study used a human confederate who walked at a consistent rate, but to four different final positions which increased the uncertainty in movement characteristics of the obstacle. Therefore, as a result of increased uncertainty in the confederate's path, it was hypothesized that individuals would use a consistent TTC to regulate their time of avoidance and change their path at a consistent temporal distance from the approaching person.

As previously suggested, obstacle avoidance actions are determined by an individuals' opportunity for action (affordance). These opportunities are dependent on the environment and the individual (i.e. body size and capabilities) (Fajen, 2013; Gibson, 1979). More specifically, individuals use body-scaled visual information to specify the environment with respect to their body dimensions. Therefore, someone who is taller (increased eye-height) and wider (greater shoulder width) will avoid an obstacle differently than someone who is shorter and smaller using behaviours relative to their body-size. Furthermore, Cinelli & Patla (2007) found that magnitude of lateral deviation at the time of crossing (i.e. ML spatial requirement) was consistent across all of the obstacle's approach velocities. Therefore, once a change in path has occurred, it was expected that the space maintained between the approaching person and the participant at time of passing (ML spatial requirement) will be determined by the sex (i.e. body size) of the participant as opposed to the actions of the approaching person (i.e. path selection).

The findings from Cinelli and Patla (2007) suggest that individuals regulate the magnitude of lateral deviation (ML spatial requirement) at the time of crossing in order to maintain consistency across the obstacle's approach velocity. In order to do so, the individuals modulated the rate at which they avoided the obstacle (i.e., ML rate of avoidance increased the faster the obstacle approached). This suggests that as the risk of collision increases (i.e. increased approach velocity), an individual will avoid an approaching obstacle faster. Within the current study, the confederate walked along four predetermined (although unknown to the participant) pathways. It was specifically stated that participants were required to avoid the approaching confederate. As such, when the confederate walked along the midline, the participant was at the greatest risk for a head-on collision if they did not change their path. Therefore, it was hypothesized that participants would avoid the approaching person at a greater rate when the confederate approached along the midline.

2.2 Methodology

2.2.1. Participants

Twenty young adults ($\bar{x}$= 22.25 ± 1.5 years, 10 males and 10 females) participated in the experiment (Table 1). Participants were recruited from a convenience sample of students from universities in the Waterloo region. Participants were not included if any of the following characteristics were present: 1) self-reported neurological disorders or deficits that affect postural control; 2) musculoskeletal injuries that may limit their ability to walk a 10 metre pathway unassisted for up to an hour; and 3) self-reported visual impairment which could not be corrected to a minimum of 20/70. Furthermore, participants were excluded if they had trained for a team field sport at a competitive or varsity level in the previous five years. The exclusion activities included soccer, field hockey, lacrosse, rugby, hockey, and basketball.

In addition to the twenty young adult participants, a confederate was used as the human obstacle throughout the experiment. The confederate was a female research assistant who was trained to maintain consistent behaviour across all trials and participants. As a result of available resources, this experiment only used a female confederate. The role of the confederate remained a secret to the participants throughout the experiment. More specifically, she was introduced to each participant as if she herself was also a participant. This was done to ensure participants' behaviours were not affected by the presence of a research assistant, but rather they treated her as they would any stranger on the sidewalk. As such, it was critical that each participant had not previously met the research assistant, and they were unknown to each other prior to the beginning of data collection. In order to maintain consistency and secrecy of the confederate's role in the experiment, the confederate was addressed in the same manner as the participant. Therefore, she completed informed consent, experimental set-up, and received the same procedural explanation as the participant before the start of every data collection session. Furthermore, to ensure consistency in gait behaviours, she wore headphones which played a metronome to maintain her cadence. In addition, to hide her gaze behaviours from the participant, the confederate wore sunglasses.

Table 1: Characteristics of young adults including sex, age, height, weight, and shoulder width.

Participant	**Sex**	**Age**	**Height (cm)**	**Weight (kg)**	**Shoulder Width (cm)**
Confederate	F	20	178	63.5	38
Male Young Adults					
1	M	24	178	70.15	40
2	M	23	172.72	63.64	39
3	M	22	177.8	72.73	40
4	M	23	185.42	75	46
5	M	23	187.96	75	41
6	M	20	188	88.64	44
7	M	22	177.8	88.64	43
8	M	24	180.34	78.18	42
9	M	24	175.26	79.55	42
10	M	21	182.88	95.5	44
Average	--------	22.6	180.62	78.70	42.10
SD	--------	1.35	5.28	9.67	2.18
Female Young Adults					
11	F	23	167.64	79.55	38
12	F	22	170.18	83.18	39
13	F	20	177.8	91.82	38
14	F	22	157.48	57.27	36
15	F	21	180.34	70.24	38
16	F	24	175.26	68.18	37
17	F	20	157.48	70.24	39
18	F	24	170.18	53.64	36
19	F	20	165.10	62.27	36
20	F	23	170	65.91	37
Average	--------	21.9	169.15	70.23	37.13
SD	--------	1.60	7.68	13.36	1.13

2.2.2. Experimental Set-up

The experiment was conducted in the Lifespan PsychoMotor Behaviour (LPMB) laboratory at Wilfrid Laurier University. The experimental design was set up in a large rectangular room (14 m by 6 m) with a 10 m pathway cleared along the midline of the room. A small visible goal was located at the end of the pathway in line with the participant's starting position. A space (7 m by 2 m) resembling the confinement of a sidewalk was outlined on the ground using yellow duct-tape. The participant and confederate were instructed to not walk outside this space (Figure1a).

Kinematic data was collected using the Optotrak motion analysis system (Northern Digital Inc., Waterloo, ON) at a sampling frequency of 60 Hz. To monitor the position of each participant in space and with respect to the confederate throughout the experiment, both the participant and confederate were outfitted with a rigid body containing three Infrared Emitting Diodes (IREDs). Each participant was outfitted with a front facing marker set-up, whereas the confederate was outfitted with a rear facing marker set-up (Figure1b). The markers were mounted to the participant and confederate using a harness to ensure the markers remained secured on the sternum of the participant and the 10th thoracic vertebrae of the confederate. In addition to the rigid bodies, points were digitized on the participant's left and right glenohumeral (GH) joint and left and right anterior superior iliac spine (ASIS), as well as the confederate's left and right glenohumeral (GH) joint and left and right posterior superior iliac spine (PSIS).

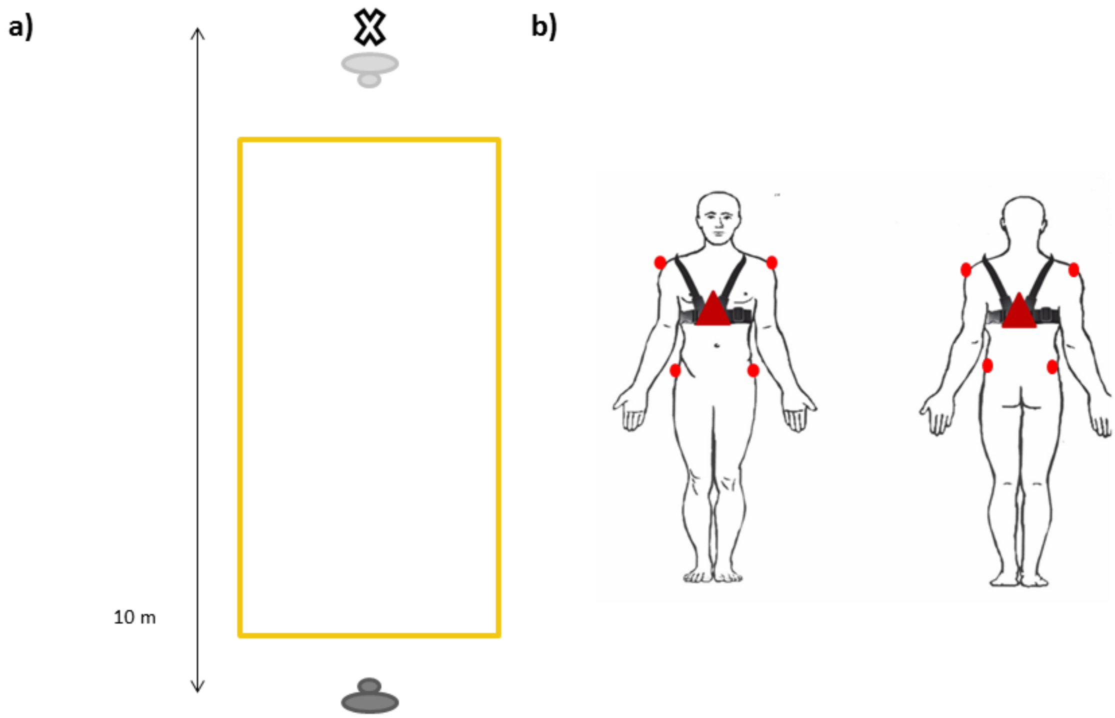

Figure 1a) Experimental space including a 2m x 7m space outlined in yellow duct tape. Participants were instructed not to leave this area to more realistically simulate a side walk. A visible goal (X) was located along the midline 10 m from the participant. The participant and confederate began each trial along the midline of the path, 180° from one another.
b) Experimental Marker set-up, including participant (left) and confederate (right).

2.2.3. Procedure

Prior to the start of each trial, the confederate stood facing the participant, 10m away from the participant's starting location, in front of the participant's goal. The participant was instructed to walk at their normal pace towards the goal without colliding with the approaching person (i.e., confederate). More specifically, the participants were assigned the role of "the avoider" in which they had to avoid colliding with the confederate, "the avoided". However, no explicit instructions were provided as to how to avoid the confederate.

The participant and confederate began moving simultaneously. At 2.5 m from her starting location, the confederate initiated a change in path to one of four predetermined positions. The positions included: 1) 1m to the left of the participant's starting position; 2) along the midline of the pathway in-line with the participant's starting position; 3) 1m to the right of the participant's starting position; or 4) stopped along the midline 2.5 m from her start position. Participants completed 10 trials of each condition, presented in a random order, for a total of 40 experimental trials. Breaks were permitted as desired between trials. Following the experiment, a debrief was conducted with each participant in order to explain the role of the confederate and the necessity of secrecy with respect to her role.

2.2.4. Data Analysis

The location of each participant's COM was calculated using a weighted average of the ML and AP coordinates of the digitized points (i.e., 0.25*left shoulder + 0.25*right shoulder + 0.25*left ASIS/PSIS + 0.25*right ASIS/PSIS). This estimate allowed for the calculation of:

1. ML spatial requirement: absolute medial-lateral (ML) distance (cm) between the closest passing shoulders of the participant and confederate at time of passing each other.

2. Change in travel path (time of avoidance): the point in time from a participant's steady state locomotion to when the participant's ML COM position fell and stayed outside 2 standard deviations of their starting position (i.e., midline of pathway). This variable was used in order to calculate the rate of ML avoidance, time to ML spatial requirement and theoretical time of collision.

3. Rate of ML avoidance: the speed (cm/s) at which the participants moved in the ML direction (from time of change in travel path to time of passing) to avoid the confederate.

4. Time to ML spatial requirement: the time (s) in which it took the participants to reach their ML position at time of passing. This value was calculated using the ML spatial requirement (cm) and rate of ML avoidance (cm/s). This time is calculated from the time of avoidance to time of crossing.

5. Time to Contact (TTC): the time (s) that remained before a theoretical collision would occur between the confederate and participant had they both continued to walk at their average speed. Speed of the confederate and the participant was calculated using an average of the instantaneous velocities across 100 frames during the approach phase up until time of avoidance. Approach phase was calculated once individuals reached steady state.

$$TTC = \frac{\text{distance between participant and confederate at time of avoidance}}{(speed\ of\ participant)+(speed\ of\ confederate)}.$$

In order to diminish the effects of extreme values, the median value from the 10 trials of each of the four conditions was used to examine the above variables. The median value was used in order to provide a more representative value for each participant's behaviour. Standard deviations from the mean of the median values discussed above were calculated to represent variability in the participants' behaviours.

2.2.5. Statistical Analysis

In order to determine whether the confederate's travel path (4) and/or the sex (2) of the participants had an effect on the outcome measures, a mixed repeated measures analysis of variance (ANOVA) was conducted. This analysis was completed for all kinematic variables discussed above. Effect size was reported using partial eta squared. Additionally, a Tukey's HSD post-hoc analysis was completed to identify where the significant differences existed as a result of the confederate's travel paths.

2.3 Results

Overall, no collision occurred between the participants and the confederate throughout the experiment. Results revealed the confederate walked 119.88 ± 7.47 cm/s throughout the experiment. The physical differences between the males and females were determined using an independent t-test. Results revealed males were significantly taller (180.6 ± 5.28 cm) than females (169.1 ± 7.58 cm), $t(18)=3.89$, $p<.001$. Furthermore, males had significantly larger shoulder widths (42.1 ± 2.18 cm) compared to females (37.4 ± 1.13 cm), $t(18)=6.00$, $p<.0001$. However, there was no significant difference in weight between males (78.7 ± 9.67 kg) and females (69.73 ± 13.16 kg) ($p=.104$) (Table 1). Furthermore, there were no significant interactions found across all variables, as such only the main effects will be discussed further.

Figure 2 shows representative raw paths of both the confederate and one participant. These figures display the location of change in travel path (time of avoidance) and ML spatial requirement for each condition.

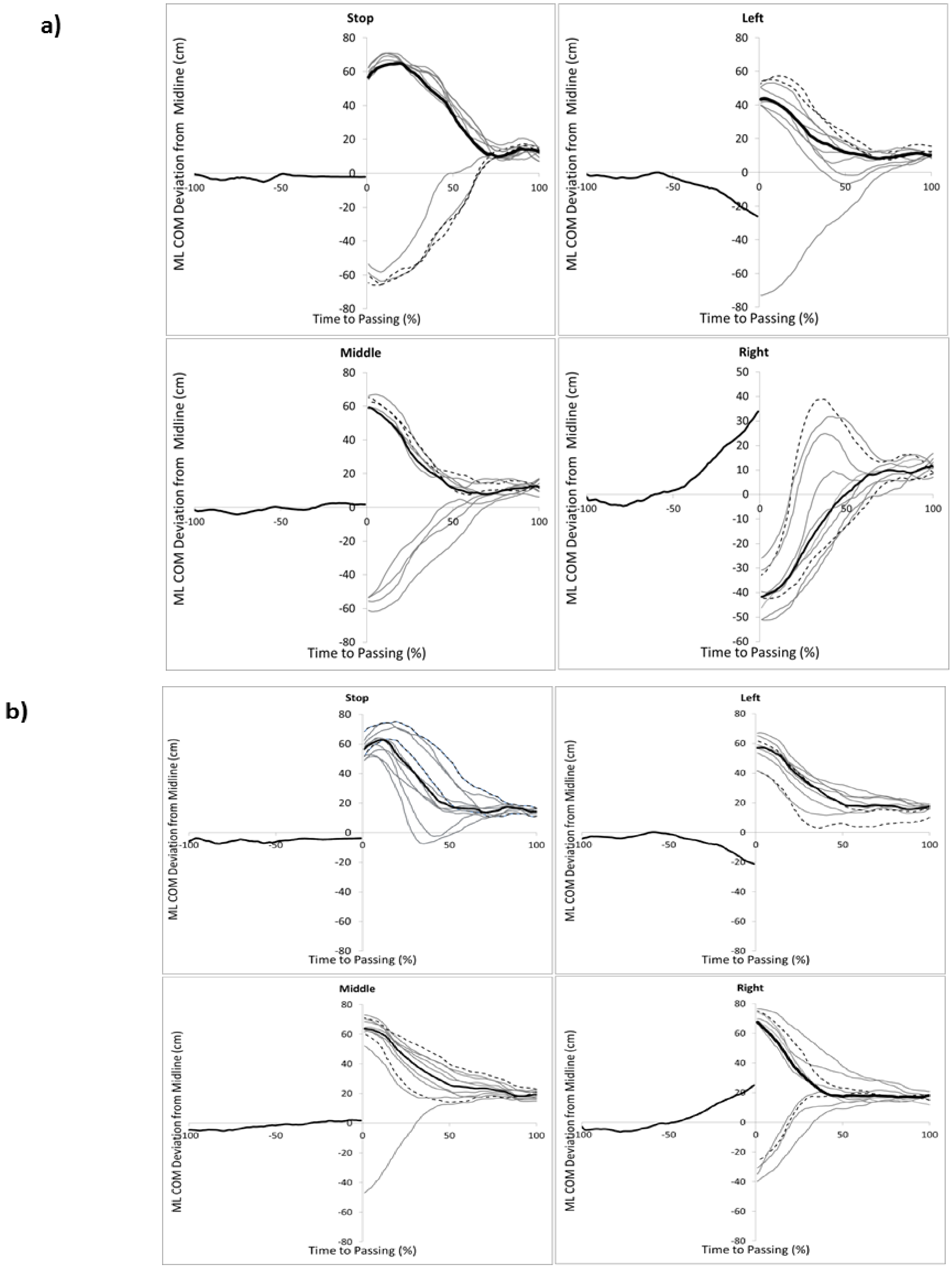

Figure 2: Paths of the confederate (black) and representative **a)** male and **b)** female participants across all path conditions. Figures displayed (from top left to bottom right) the stop, left, middle, and right confederate path conditions, respectively. Ten trials for each condition are depicted, the median of the condition is illustrated with the bolded line, and trials 1 and 10 are illustrated with dashed lines. Trials are illustrated as a percent of time to passing, such that 100% represents beginning of the trial and 0% represents time of passing.

2.3.1. Time to Contact (TTC)

Time to contact describes the temporal proximity prior to colliding with the approaching confederate had the participants not deviated from the collision course. As such, TTC provides insights as to whether an optical expansion threshold, which is directly perceived, was used to determine the timing of avoidance behaviours. Cinelli and Patla (2007) observed that despite different velocities of the approaching obstacle, participants changed travel path at the same location in the room and not relative to the obstacle. However, the path of the confederate was highly predictable, therefore individuals did not use a consistent TTC (Cinelli & Patla, 2007). Since the obstacle (confederate) in the current study walked along multiple randomized paths (i.e., unpredictable to the participant), it was hypothesized that individuals would use a consistent TTC and change their paths at a consistent temporal distance from the confederate. However, a Mixed Repeated Measures ANOVA revealed a main effect of confederate path on TTC ($F_{(3,54)}$=6.43, $p<.001$, η^2=.263). A Tukey's HSD post-hoc analysis determined participants avoided earlier when the confederate stopped 2.5 m from her starting position (1.98 ± 0.54 s) compared to the left path (1.55 ± 0.54 s), the middle path (1.73 ± 0.60 s), and the right path (1.78 ± 0.50 s) ($p<.001$, $p<.05$, $p<.05$, respectively). In addition, participants avoided earlier when the confederate moved to the right than the left ($p<.05$) (Figure 3a).

Additionally, Hackney and colleagues (2015) observed a trend in greater spatial requirements for males compared to females while passing through a gap composed of female obstacles (Hackney, Cinelli, et al., 2015). In turn, it was hypothesized that males would avoid the female confederate earlier (i.e., greater TTC) than females to increase AP spatial requirements. Results revealed a main effect of sex ($F_{(1,18)}$=6.68, $p<.05$, η^2=.271), such that males avoided significantly earlier than females (1.99 ± 0.22 s and 1.52 ± 0.19 s, respectively) (Figure 3b).

Additionally, Table 2 depicts the median and within-subject variability for each participant in the primary outcome, TTC.

Table 2: Within-subject variability across each confederate path condition for TTC.

Participant	$Stop_{Median}$	$Stop_{SD}$	$Left_{Median}$	$Left_{SD}$	$Middle_{Median}$	$Middle_{SD}$	$Right_{Median}$	$Right_{SD}$
Female Young Adults								
1	1.69	0.74	0.85	0.30	0.76	1.01	1.77	0.65
2	1.15	0.84	1.14	0.55	1.24	0.74	1.17	0.41
3	2.40	0.54	1.20	0.35	1.32	1.06	1.80	1.96
4	1.92	0.77	1.54	1.00	2.79	0.79	1.41	0.75
5	1.74	0.73	1.50	0.76	1.08	0.23	1.16	0.83
6	1.93	0.57	1.94	0.56	1.76	0.45	1.95	0.50
7	1.74	0.53	1.81	0.69	1.54	0.46	2.00	0.73
8	1.10	0.46	1.20	0.74	1.39	0.60	1.15	0.69
9	1.26	0.37	1.13	0.58	0.92	0.35	1.72	0.86
10	1.98	0.54	1.43	0.49	1.71	0.51	1.51	0.43
Male Young Adults								
1	1.36	0.52	0.88	0.28	0.98	0.45	1.00	0.57
2	2.36	0.47	1.85	0.58	2.05	0.98	2.34	0.49
3	2.75	0.66	2.71	0.33	2.75	0.57	2.64	0.22
4	2.60	0.54	1.20	0.71	1.89	0.73	1.95	1.45
5	2.61	0.37	1.10	0.78	2.23	0.54	2.45	0.63
6	2.29	0.42	2.04	0.39	2.08	0.24	2.10	0.20
7	1.98	0.56	1.58	0.57	1.68	0.65	1.91	0.69
8	2.71	1.25	2.38	0.44	2.07	1.23	1.98	0.43
9	1.48	0.31	1.04	0.75	1.67	0.78	1.12	0.75
10	2.54	0.36	2.44	0.41	2.66	0.21	2.48	0.61

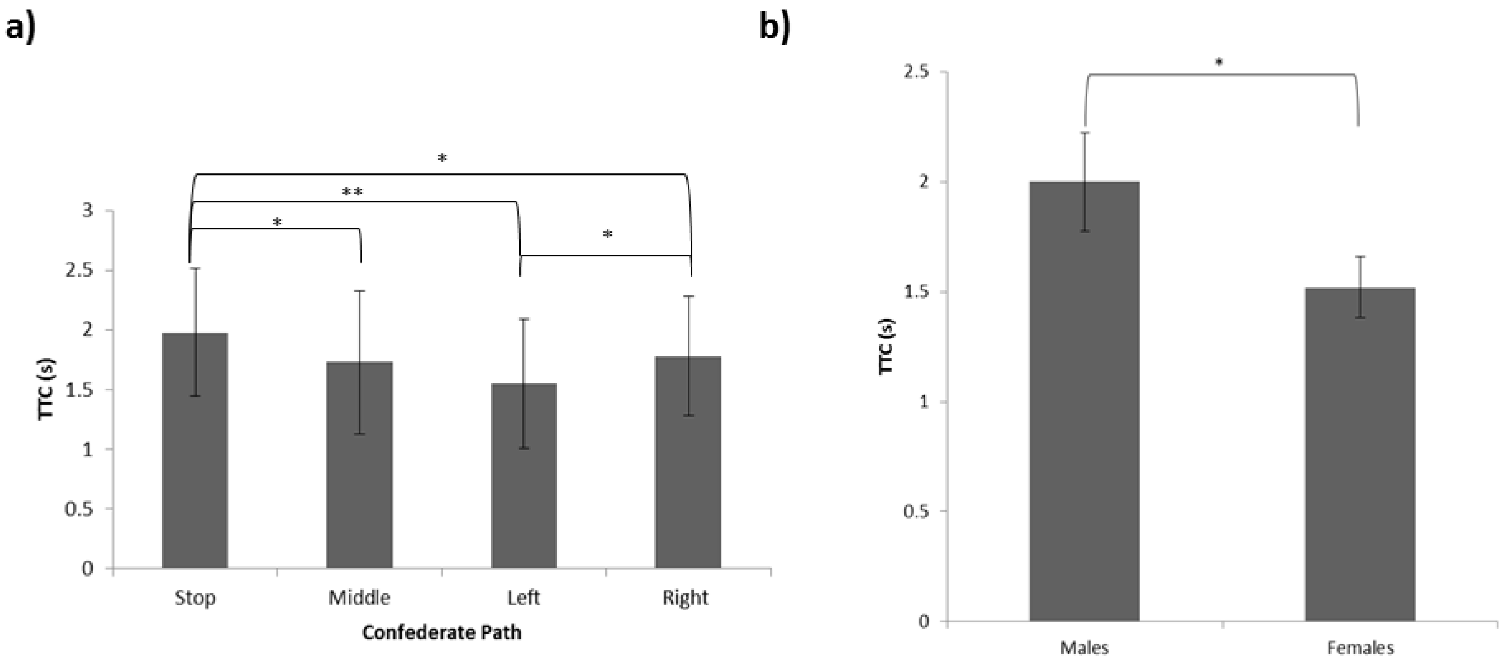

Figure 3: a) Time to contact (TTC) describes the temporal proximity prior to colliding with the approaching confederate when the participant initiated a change in path. This figure shows the average median TTC (seconds; with SD bars), which was significantly earlier when the confederate stopped 2.5 m from her starting position compared to the middle, left and right paths ($p<.001$, $p<.05$, $p<.05$, respectively). Additionally, participants avoided earlier when the confederate moved to the left than the right ($p<.05$) **b)** Males avoided significantly earlier than females ($p<.05$).

2.3.2. ML Spatial Requirement

The affordance based model of obstacle avoidance suggests that individuals consider their relative body dimensions during obstacle avoidance (Fajen, 2013). More specifically, an individual with a larger body size must move farther than someone with a smaller body size in order to avoid the same obstacle (Fajen, 2013). In turn, it was hypothesized that ML spatial requirement would not be affected by the path of the confederate, but rather the sex (i.e. size) of the participant. However, contrary to the hypothesis, the results revealed a main effect of confederate path, $F_{(1.58,28.48)}=7.81$, $p<.01$, $\eta^2=.303$. A Tukey's HSD post-hoc analysis identified that participants maintained a significantly greater ML spatial requirement when the confederate moved to the left (31.6 ± 14.51 cm) compared to both the stop (22.7 ± 11.44 cm) and middle (20.9 ± 11.53 cm) path conditions ($p<.0001$) (Figure 4a). Furthermore, results revealed no significant difference between males (29.42 ± 5.51 cm) and females (21.44 ± 4.11 cm) in ML spatial requirement ($p=.11$) (Figure 4b).

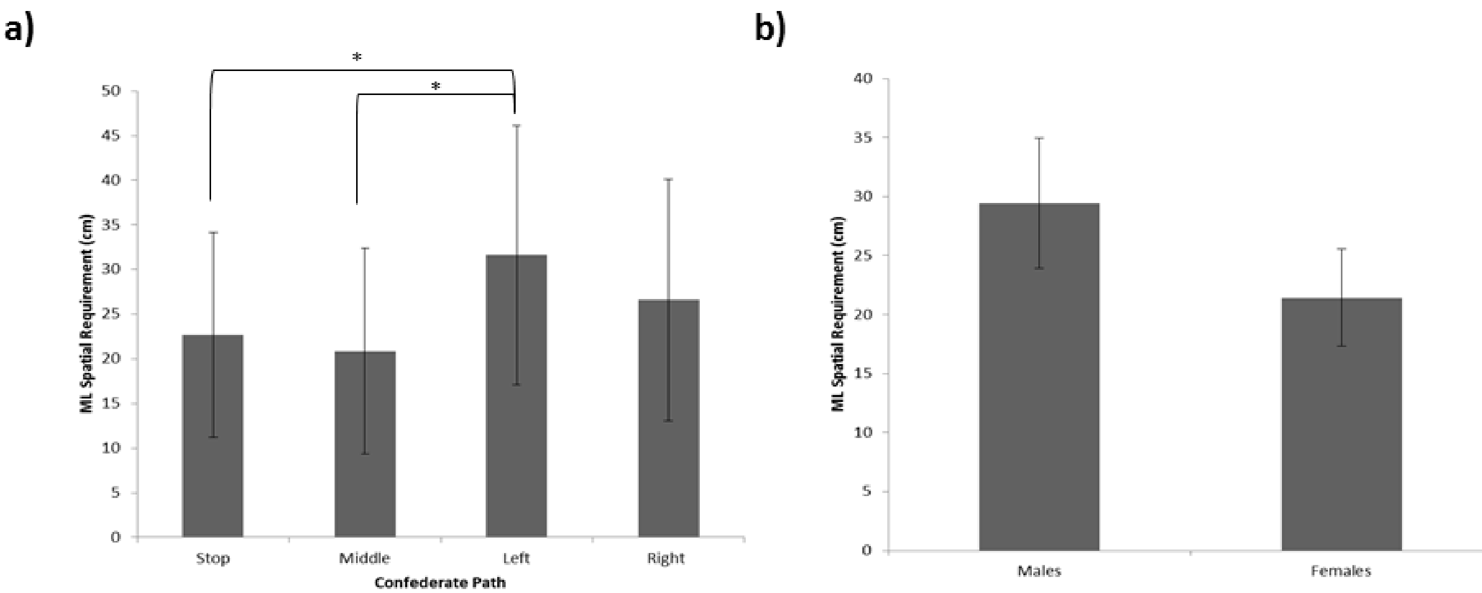

Figure 4: a) ML spatial requirement was the absolute ML distance between the participant's and confederate's closest shoulders at time of crossing. The figure shows the average median spatial requirement (centimetres; with SD bars), which was significantly larger when the confederate moved to the left compared to the stop and middle path conditions ($p<.0001$). **b)** ML spatial requirement was not difference between males and females ($p=.11$)

2.3.3. ML Rate of Avoidance

When the confederate approached the participant along the midline, the participant and the confederate remained on a collision course until the participant initiated a change in path. Therefore, the greatest risk of collision existed during the middle condition. Since TTC is assumed to be consistent across all path conditions, it was hypothesized that participants would avoid the confederate at a greater rate when the confederate approached along the midline in order to mitigate the risk of collision. Results revealed a significant main effect of confederate path on ML rate of avoidance ($F_{(3,54)}$=22.12, p<.01, η^2=.303), such that the participants avoided the confederate at a significantly faster rate when the confederate walked along the midline (21.61 ± 4.34 cm/s) compared to the left (18.43 ± 5.22 cm/s) and stop (14.62 ± 4.78 cm/s) path conditions (p<.01 and p<.0001, respectively). Furthermore, the ML rate of avoidance was significantly faster when the confederate walked to the right (22.93 ± 5.02 cm/s) of the participant compared to the left and stop path conditions (p<.01 and p<.0001, respectively). Additionally, the ML rate of avoidance was significantly slower when the confederate stopped compared to all other path conditions (p<.0001) (Figure 5a). Furthermore, results revealed no significant difference between the ML rate of avoidance of males (18.87 ± 4.29 cm/s) and females (19.93 ± 0.56 cm/s) (p=.54) (Figure 5b).

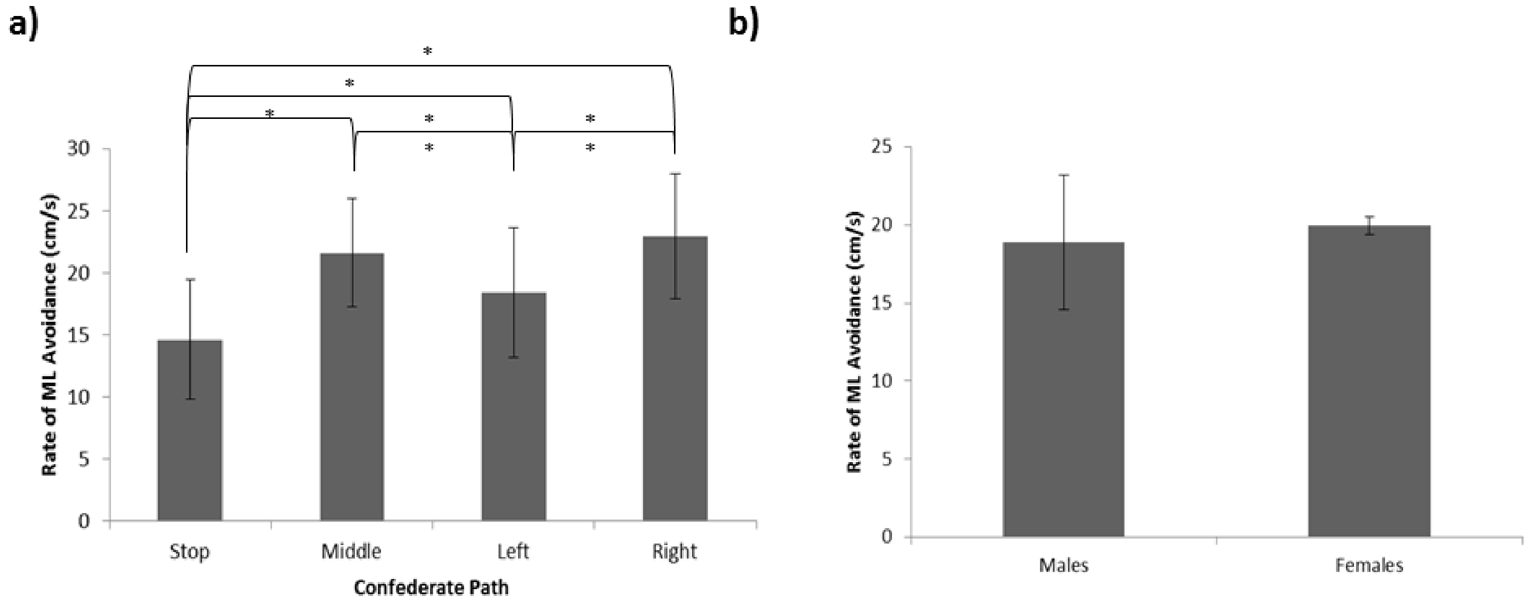

Figure 5: a) ML rate of avoidance describes the speed at which participants moved in the ML direction to avoid the confederate. The figures shows the average median speed (centimetres/second; with SD bars), which was fastest when the confederate walked along the midline compared to left (p<.01) and stop (p<.0001) path conditions. **b)** ML rate of avoidance was not different between males and females (p=.54)

2.3.4. Time to ML Spatial Requirement

In order to observe the temporal control of the individuals' avoidance behaviours, the time to reach their ML spatial requirement was calculated. Results revealed a significant main effect of confederate path ($F_{(1.785,32.128)}=10.06$, $p<.001$, $\eta^2=.358$). A post hoc analysis identified participants took more time to avoid when the confederate was stopped (1.79 ± 1.34 s) then when the confederate walked down the middle (1.05 ± 0.76 s) or to the right (1.20 ±0.67 s) (p<.0001 and p<.05, respectively). Additionally, confederated took more time to avoid when the confederate walked to the left (1.9 ± 1.14 s) than the middle (p<.0001) and right (p<.05) (Figure

6a). Furthermore, there were no significant differences in the time it took males (1.81 ± 0.54 s) and females (1.16 ± 0.34 s) to reach their ML spatial requirement (p=.09) (Figure 6b).

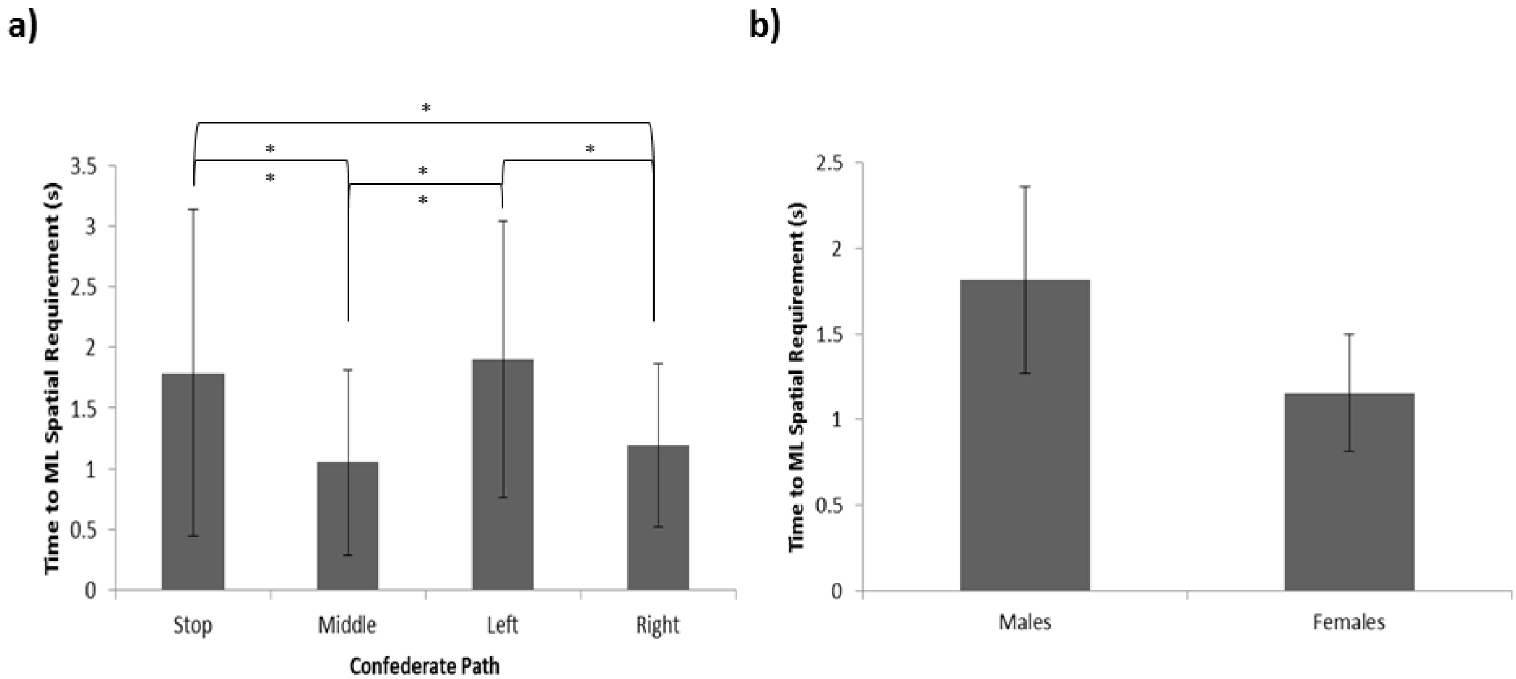

Figure 6: a) Time to ML spatial requirement depicts the time it took the participant to reach their ML spatial requirement at time of crossing. The figures shows the average median time (seconds; with SD bars), which was slowest when the confederate stopped compared to when the confederate walked down the middle ($p<.0001$) or right ($p<.05$). Additionally, participants took more time to avoid when the confederate moved to the left than the middle ($p<.0001$) and right ($p<.05$). **b)** Time to ML spatial requirement was not different across males and females (p=.09).

2.4 Discussion

The objective of the current study was to examine the avoidance strategies of young adults walking along a head-on (180^{o}) collision course with an approaching person. Consistent with previous literature, the current study demonstrated that individuals' avoidance behaviours are guided by an elliptical shaped protective zone (Figure 7) (Gérin-Lajoie, Richards, Fung, &

McFadyen, 2008; Gérin-Lajoie et al., 2005; Hackney et al., 2013). The protective zone in the current study appears to be governed by both the time at which individuals avoided (AP dimension), as well as the space maintained in the ML direction at time of crossing the other person. The time at which individuals avoided (i.e. AP temporal requirements) can be thought of as the "when" and once a change in path was produced, the remaining avoidance behaviours (i.e. ML spatial requirement, ML rate of avoidance, and time to ML spatial requirement) can be thought of as "how" individuals avoided the confederate.

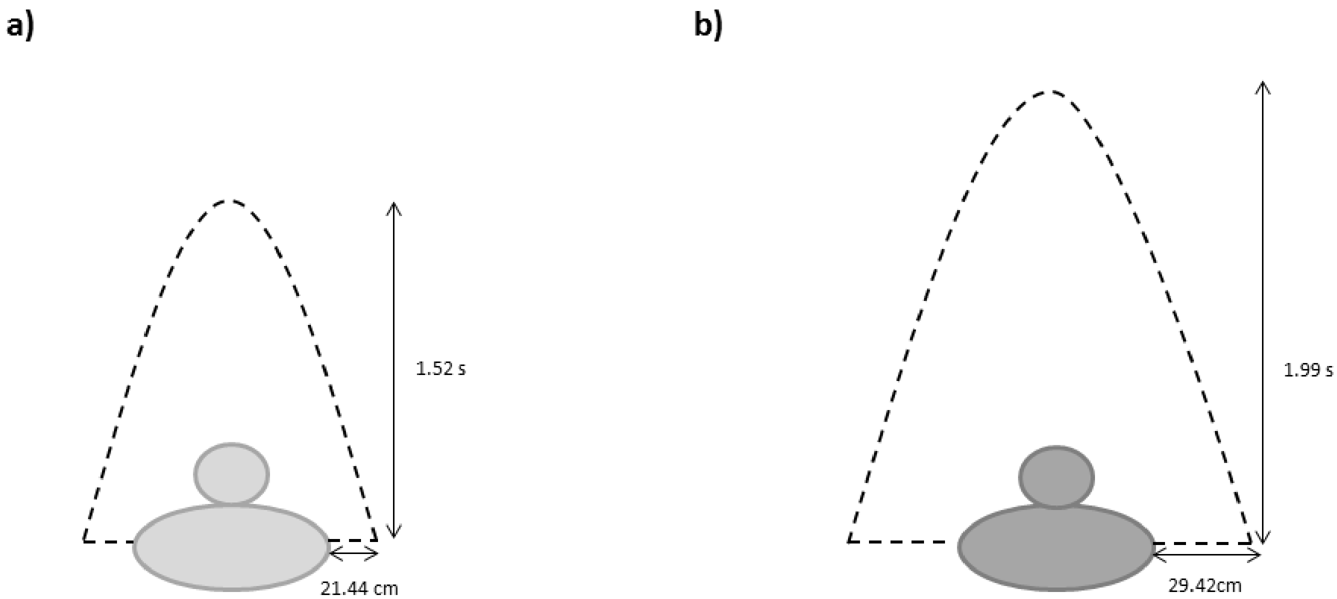

Figure 7: Average protective zone maintained by **a)** female and **b)** male participants across all confederate path conditions. Males maintained a significantly greater temporal space between themselves and the confederate compared to females ($p<0.05$).

2.4.1. Time to Contact (TTC) ("When")

Time to contact (TTC) is the theoretical time in which two objects on a collision course will collide if both move at a constant speed. Lee (1974) suggested that *tau* (τ) would be the optical variable used to determine TTC and guide the timing of avoidance behaviours if the approach of the object was consistent (Lee, 1974). Unlike the findings from Cinelli & Patla (2007), the current study believed that if the rate of the approaching obstacle was constant, but the pathway was unpredictable, individuals would keep TTC consistent across conditions as a measure of their AP protective zone. Findings suggest that when the path of the confederate was unpredictable, participants maintained a consistent TTC at the point of path deviation. However, when the confederate stopped 2.5 m from her starting location, participants avoided significantly earlier compared to all other path conditions (Figure 3a). Individuals may not have used a consistent TTC when the confederate stopped due to the decrease in ambiguity of the confederate's movements. This result is consistent with that of Cinelli & Patla (2007) who found that when the path of an approaching obstacle is known, individuals do not maintain a consistent TTC. Furthermore, protective zones are greater when approaching a stationary obstacle compared to a moving obstacle (Gérin-Lajoie et al., 2005). Therefore, when the confederate stopped 2.5 m from her starting location, her trajectory became apparent to the participants, which increased the predictability in her movements (or lack thereof). This finding suggests that when there is certainty in a moving obstacle's trajectories, individuals do not need to maintain a consistent TTC when producing a change in pathways.

During the conditions in which the confederate's trajectory was uncertain (i.e. the three remaining path conditions), individuals regulated their time of avoidance by using a relatively consistent TTC. The current study found that the only difference in time of avoidance within these path trajectories occurred between the trials in which the confederate walked to the left and right of the participant. More specifically, participants avoided significantly earlier when the confederate moved to the right of the participant compared to the left of the participant. This behaviour may have occurred as a result of an asymmetry between right and left visual fields in their detection of movement (Kostelyanets, Kamenkovich, & Sharaev, 1992). During a visual search paradigm, it has been found that reaction time is significantly faster for targets presented in the right visual field compared to the left (Christman & Naegele, 1995). As such, individuals may have been able to process the movement of the confederate in their right visual field faster, leading to an earlier avoidance. It can be argued that individuals used the optical variable *tau* to determine when to avoid the approaching confederate and maintain a relatively consistent protective zone; however only when the pathway of the obstacle (confederate) was uncertain.

Differences between observers may also impact how individuals use *tau* or TTC information. The results confirmed that males avoided the confederate significantly earlier than females (Figure 3b), which was in line with the hypothesis. As previously discussed, males had significantly wider shoulder widths than the females. Therefore, in order to reach the desired ML spatial requirement at the time of passing without colliding with the confederate, male participants were required to travel further medial-laterally. However, it is important to note that the ML rate of avoidance was not significantly different across males and females (Figure 4b). Consequently, to avoid colliding with the confederate within the same time frame and to the same ML magnitude of the female participants, males were required to avoid significantly earlier. This result is in line with the affordance-based model of obstacle avoidance proposed by Fajen (2013) and further supports the idea that individuals take both their widest body dimension (shoulder width) and locomotor capabilities into account while employing avoidance strategies. Additionally, there were no interactions between the confederate path trajectories and the participant groups. Therefore, it can be concluded that both males and females use TTC information (*tau)* to drive their time of avoidance when the path of the confederate was unknown. However, males have a smaller optical expansion threshold than females when avoiding an approaching a female confederate within a confined space and therefore need to avoid earlier.

2.4.2. Avoidance strategies ("How")

Following a change in path ("when"), individuals must also determine how they will avoid an approaching object (i.e., confederate in the case of the current study). Individuals may control spatial and/or temporal components of their avoidance behaviours, including their ML spatial requirements, rate of avoidance, as well as time to ML spatial requirement.

Originally, it was hypothesized that the sex of the participant, as opposed to path of the confederate, would drive ML spatial requirement. Contrary to the hypothesis, males and females did not display a significant difference in ML spatial requirement. However, the path of the confederate significantly influenced ML spatial requirement such that participants maintained a smaller ML spatial requirement when the confederate either walked along the midline or stopped 2.5 m from her starting position compared to the left path (Figure 4a). This result is in line with the behaviour dynamics theory proposed by Fajen and Warren (2003); such that path selection was a function of the relative angles and distances between the individual's instantaneous position, the obstacle, and the goal. Participants in the current study considered their interaction with both the goal and the approaching obstacle (confederate), as well as the task instructions (i.e. stay within the yellow tape) in order to efficiently avoid the approaching obstacle. Additionally, individuals' path selections are driven primarily by the goal as opposed to a human obstacle (Pfaff & Cinelli, 2016). As a result, in order to successfully reach the goal when it was located behind and in line with the confederate's path trajectory, individuals maintained a significantly smaller ML spatial requirement than when the confederate moved to the left. This finding is further supported by the affordance competition hypothesis which suggests individuals consider specifications of potential action (i.e., avoiding the approaching confederate to a particular magnitude) and is modulated by decision variables (Cisek, 2007). Therefore, individuals considered the potential actions of avoiding the approaching confederate and reaching the goal in conjunction with one another. Alternatively, this finding may have occurred because of the environmental constraints illustrated by the yellow tape on the floor. This constraint was greatest when the confederate was walking along the midline. Additionally, ML spatial requirements were greater when the confederate moved to the left because as the confederate moved to the left and the participant avoided on the right, each person was increasing the space between them mutually. This finding is similar to that of Olivier and colleagues (2012) who illustrated that avoidances are guided by reciprocal interactions and are dependent on both parties (Olivier, Marin, Crétual, & Pettré, 2012).

Contrary to the hypothesis, the current study did not find a significant difference in ML spatial requirement between males and females (Figure 4b). The force of impact following a collision is a product of the mass and velocity of the colliding components; as a result, the greater the mass, the greater the impact. However, participant demographics revealed that the males did not have a significantly greater mass than the female group, therefore from a collision standpoint; neither group would have created a greater impact on the confederate in the instance of a collision. Since this was the case, it is not surprising that males and females had similar ML spatial requirements at the time of passing. This finding is similar to Hackney, Cinelli & Frank (2015) which found that males maintained a greater, non-significant ML spatial requirement while passing through an aperture composed of two females.

It is clear participants did not regulate the spatial components of their avoidance, however they may have modulated temporal components instead. Based on the instructions provided during the experiment, the participants were required to initiate all avoidance behaviours allowing the confederate to walk along her desired path. As such, the condition in which the participant walked along the middle of the pathway provided the greatest risk of collision if the participant did not change their path. For this reason, it was hypothesized that participants would avoid the confederate at a faster rate when the confederate walked along the midline in order to reduce the threat of collision. Findings from the current study confirmed that participants avoided the confederate at a significantly faster rate when the confederate walked along the midline compared to when she walked to the left or stopped. Therefore, when the threat for collision is greater (i.e. increased approaching velocity), individuals will avoid the obstacle at a faster rate (Cinelli & Patla, 2007). Additionally, results revealed participants avoided at a faster rate when the confederate moved to the right compared to the left and when she stopped. When the confederate moved to the right, it decreased the available space for rightward passage. In North America, individuals typically pass on the right (during driving and sidewalk scenarios), as such when the confederate walked to the right and the participants were forced to avoid to the left, they may have felt more uncomfortable and therefore may have moved at a faster rate. Finally, the findings from the current study revealed that participants avoided the confederate significantly slower when she stopped 2.5 m from her starting location than all other conditions. Similarly to the TTC findings, individuals may have avoided the confederate at a slower rate because there was less uncertainty in her movements and in turn a reduced threat of collision. Again, during the instances when the confederate stopped, her lack in movement may have resulted in the participants treating her like a stationary obstacle. Despite treating the confederate like a stationary obstacle with respect to protective zone (i.e. increased TTC and ML spatial requirement), the difference in the rate of avoidance is in contrast to previous research which found that individuals avoid a moving obstacle significantly slower than a stationary obstacle (Gérin-Lajoie et al., 2005).

Since the individuals are not consistently controlling their ML spatial requirements or rate of avoidance, it is possible that they controlled the time to which they reached their ML spatial requirement. However, the results revealed that the time it took to reach the ML spatial requirement was not consistent across path conditions. More specifically, individuals took more time to reach their ML spatial requirement when the confederate was stopped 2.5 m from the starting location compared to walking along the midline of the pathway or to the right of the participant. This behaviour may have been observed as a result of experimental set-up. The participants may have taken longer to reach their ML spatial requirement due to the fact that the confederate was stopped further from them at time of avoidance. Additionally, individuals took more time to reach their ML spatial requirement when the confederate walked to the left of the participant compared to along the midline and to the right of the participant. These findings suggested that the regulating factor in individuals' avoidance behaviours are not consistent across the confederate's path trajectories, but rather are determined using on-line control within dynamically changing environments.

Overall, when looking at the avoidance behaviours completely, it was found that individuals may have selected a strategy based on comfort. More specifically, when the confederate was stopped 2.5 m from her starting location, the participants avoided earlier, moved slower, and took more time to reach their smaller ML spatial requirement than during the other path conditions. As such, when the confederate's position and movement (or lack thereof) is known *a priori* there is less uncertainty in the situation and participants may have been more comfortable in making avoidance behaviours. Additionally, when comparing the conditions in which the confederate moved to the extremes (i.e. left or right path conditions), avoidance strategies suggested individuals were more comfortable when the approaching confederate moved to the left of the participants. More specifically, the participants avoided the confederate at a slower rate, later, and took longer to reach their spatial avoidance when the confederate was moving to the left. This falls in line with societal norms in which individuals typically move to their right when passing objects.

It is important to note that the sex of the participant did not have an effect on ML spatial requirement, rate of avoidance, or time to ML spatial requirement. The current study was unable to deduce the effect of sex on the avoidance behaviours of the males and females beyond the impact of physical characteristics that differ across the groups. Additionally, the current study only used a female confederate. This is in line with previous research which examined the effects of female human obstacles on critical point (Hackney et al., 2015). Future research should look to examine the potential differences in avoidance behaviours of a male obstacle. Previous research has suggested that a multitude of factors including sex, familiarity to the human obstacle, and culture may contribute to personal space (Beaulieu, 2004; Pedersen & Heaston, 1972); however, the effect of social factors extends beyond the scope of this thesis.

2.5 Conclusion

The current study found that both changes to the environment and the observer impacted obstacle avoidance of an approaching person; however a single strategy or solution was not maintained throughout the experiment. In order to determine when to initiate a change in path, individuals used a consistent TTC when the path of the confederate was uncertain. Furthermore, TTC was impacted by the observers' body-scaled information and differed between males and females. However, overall, the "hows" of avoidance were not impacted by the observer, but rather the environment and task constraints. Behaviours were not consistent across all paths of the confederate, and therefore individuals employed a number of different strategies in order to avoid the approaching person. This suggests that aside from the timing of an avoidance, strategies and the protective zone maintained during obstacle avoidance are impacted by a multitude of variables and are determined using online visual control.

Chapter 3

The effects of sport specific training of rugby players on avoidance behaviours during a collision course with an approaching person

3.1 Introduction

The avoidance of another human is critical and may present more dire consequences when unsuccessful in a sport setting. Athletes are suggested to have specifically trained visual strategies in which they may extract important information from the environment (Fajen et al., 2008). Using this information, athletes have increased ability to use body- and action-scaled perceptual judgement to move efficiently throughout the world. During locomotion, the visual system provides instantaneous information from a distance. Individuals are able to use visual information in an anticipatory manner to guide their behaviours and make on-line adjustments (Higuchi, 2013). The temporal component of visual information is used to determine when to initiate movements. More specifically, individuals are able to directly perceive the time prior to colliding with an object (time to contact, TTC) (Lee et al., 1982; Lee, 1974; Savelsbergh et al., 1992). After determining when to initiate a movement, what strategies and how an individual moves is dependent on a number of features. More precisely, these strategies are based on an individual's possibilities for action (affordances), which are dependent on characteristics of the observer and physical properties of their environment (Gibson, 1979).

During obstacle avoidance, individuals maintain a protective zone which allows for time to perceive, evaluate, and react to potential hazards in their environment (Templer, 1992). Previous research suggests individuals maintain an elliptical shaped protective zone during obstacle avoidance (Cinelli & Patla, 2007; Gérin-Lajoie et al., 2005; Hackney, Van Ruymbeke, Bryden, & Cinelli, 2014). Gérin-Lajoie and colleagues (2005) found individuals maintain 2.11 metres anteriorly and 0.48 medial-laterally when avoidance a stationary obstacle. This protective zone decreased by 22% when the obstacle was moving along a predictable path to allow individuals to gather more information prior to initiating an avoidance (Gérin-Lajoie et al., 2005).

Previous literature has found controversial results regarding the avoidance behaviours of athletes. The inconsistencies suggest athletes may perform differently depending on environment constraints and form of locomotion. Higuchi and colleagues (2011) found that while running, American football players elicited smaller magnitudes and later onset shoulder rotations when passing through a gap compared to non-contact athletes. However, Hackney, Zakoor & Cinelli (2014) did not find a difference in the avoidance behaviours or path selections of athletes and non-athletes while running during a similar aperture-crossing task. The discrepancies between the two studies are most likely related to the paradigm, such that Hackney, Zakoor & Cinelli (2014) allowed individuals to pass through or around the aperture, whereas Higuchi and colleagues (2011) confined their participants to passing through the aperture. This suggests that during a non-confined obstacle avoidance task, specifically trained athletes do not display differences in their avoidance behaviours while running. Whereas, Gérin-Lajoie and colleagues (2007) found that while fast walking, athletes completed a non-confined multi-obstacle avoidance task faster and used more efficient paths than non-athletes. However, few field sports involve athletes avoiding stationary inanimate obstacles; therefore, it is critical to understand how behaviours differ when avoiding another person under sport specific environments. Pfaff & Cinelli (2017) found that regardless of the type of locomotion, rugby players chose paths furthest form the human obstacle. Additionally, while moving with a ball (i.e., walking or running), medial-lateral (ML) spatial requirements were smaller and less variable than while walking without the ball (Pfaff & Cinelli, 2017). This finding suggests the sport-specific behaviours may not be dependent on the form of locomotion, but rather moving in a sport-specific context (i.e., moving with a ball).

The current study sought to identify the effects of sport-specific training on avoidance strategies during a head-on (180°) collision course with an approaching person. Previous research has suggested individuals regulate TTC while avoiding obstacles. Cinelli & Patla (2007) examined whether individuals use a consistent TTC while avoiding a head-on collision. The path of the obstacle was highly predictable and therefore individuals changed their paths at the same location from the start position, regardless of TTC. Since the current study used a confederate who walked along one of four different paths, which were randomized and unpredictable to the participants, it was hypothesized that individuals would maintain a consistent TTC to regulate their time of avoidance and change their path at a consistent temporal distance from the approaching person. Additionally, rugby players avoided significantly later during a sport specific context (i.e., running with the ball) than while walking or walking with a ball (Pfaff & Cinelli, 2017). Since the current study presents a sport specific scenario with an approaching human obstacle, it was hypothesized that rugby players would maintain a smaller TTC than non-athletes.

As previously suggested, affordances (i.e. opportunities for action) are dependent on the fit between the environment and characteristics of the individual (including body size and action capabilities) (Fajen, 2013; Gibson, 1979). Based on the affordance-based model of obstacle avoidance, individuals consider their body dimensions and action capabilities relative to the environment during obstacle avoidance (Fajen, 2013). Individuals can use affordances to guide either the time of an avoidance or the manner in which they avoid the obstacle. Cinelli & Patla (2007) observed that individuals controlled the magnitude of lateral deviation during obstacle avoidance (i.e., ML spatial requirement) across different approach velocities of the approaching obstacle. Whereas Cinelli & Patla (2007) used a predetermined path of the approaching obstacle and altered the velocity of approach, the present study examined the effects of an unknown path on avoidance behaviour. Similarly, it was hypothesized that ML spatial requirement would not be affected by characteristics of the obstacle (i.e., path of the confederate), but rather would be impacted by an individual's action capabilities (sport-specific training). Since Higuchi and colleagues (2011) found that football players elicited smaller shoulder rotation magnitudes during aperture crossing, it was hypothesized that rugby players would maintain a significantly smaller ML spatial requirement than non-athletes at the time of crossing.

The findings from Cinelli & Patla (2007) suggest that individuals modulate the rate at which they avoid an obstacle. More specifically, as the approach speed of the obstacle increased, so did the ML rate of avoidance (Cinelli & Patla, 2007). This suggests that as the risk of a collision increases (i.e. increased approach velocity), individuals will avoid faster. The current study instructed participants to avoid the approaching confederate. More specifically, the confederate walked along a prescribed path and if the participant did not initiate the avoidance, they would collide. Therefore, of the four confederate paths, the greatest potential for a collision existed when the confederate walked along the midline. As such, it was hypothesized that individuals would avoid the approaching confederate at a faster rate when she approached along the midline. Additionally, since it is expected that the rugby players will avoid later than their non-athlete counterparts, it is expected that they will avoid the confederate at a faster rate than the non-athletes.

Since rugby players are less variable in their avoidance behaviours when moving with a ball (Pfaff & Cinelli, 2017), it was hypothesized that rugby players would be more consistent than non-athletes across all avoidance behaviours (including TTC, ML spatial requirement, and rate of ML avoidance). Athletes will be less variable in their actions in order to stay consistent with actions they find to be successful in games and practice.

3.2 Methodology

3.2.1. Participants

Ten female varsity rugby players ($\bar{x}$= 20 ± 0.94 years) and ten female non-athletes ($\bar{x}$= 21.9 ± 1.6 years) participated in the experiment (Table 1). The athletes in the current study reported to train approximately 10-15 hours per week while in season and are explicitly coached to run and advance the ball by fitting between narrow spaces. Participants were not included if any of the following exclusion criteria were present: 1) self-reported neurological disorders or deficits that affect balance control; 2) musculoskeletal injuries that may limit their ability to walk a 10 metre pathway unassisted for up to an hour; 3) self-reported visual impairment which could not be corrected to a minimum of 20/70; and 4) had sustained a concussion in the previous 6 months. In order to examine the effects of sport specific training, participants in the non-athlete group were excluded if they had trained for a team-based field sport at a competitive or varsity level in the previous five years. The exclusion activities included soccer, field hockey, lacrosse, hockey, basketball, and rugby.

In addition to the twenty young adult participants, a confederate was used as the human obstacle throughout the experiment. The confederate was a female research assistant who was trained to maintain consistent behaviour across all trials and participants. As a result of available resources, this experiment only used a female confederate. The role of the confederate remained a secret to the participants throughout the experiment. More specifically, she was introduced to each participant as if she herself was also a participant. This was done to ensure participants' behaviours were not affected by the presence of a research assistant, but rather they treated her as they would any stranger on the sidewalk. As such, it was critical that each participant had not previously met the research assistant, and they were unknown to each other prior to the beginning of data collection. In order to maintain consistency and secrecy of the confederate's role in the experiment, the confederate was addressed in the same manner as the participant. Therefore, she completed informed consent, experimental set-up, and received the same procedural explanation as the participant before the start of every data collection session. Furthermore, to ensure consistency in gait behaviours, she wore headphones which played a metronome to maintain her cadence. In addition, to hide her gaze behaviours from the participant, the confederate wore sunglasses.

Table 3: Characteristics of athletes and non-athletes including sex, age, height, weight, shoulder width, and frequency of physical activity.

Participant	**Sex**	**Age**	**Height (cm)**	**Weight (kg)**	**Shoulder Width (cm)**
Confederate	F	20	178	63.5	38
Athletes					
1	F	20	162.56	63.64	38
2	F	20	172.72	81.82	41
3	F	20	157.48	62.13	38
4	F	19	162.56	50.91	35
5	F	21	175.26	104.55	42
6	F	20	180.34	84.09	39
7	F	19	162.56	61.36	37
8	F	19	167.64	62.73	38
9	F	22	167.64	68.18	38
10	F	20	175.26	77.27	41
Average	--------	20	168.40	71.67	38.70
SD	--------	0.94	7.29	15.47	2.11
Non-athletes					
1	F	23	167.64	79.55	38
2	F	22	170.18	83.18	39
3	F	20	177.8	91.82	38
4	F	22	157.48	57.27	36
5	F	21	180.34	70.24	38
6	F	24	175.26	68.18	37
7	F	20	157.48	70.24	39
8	F	24	170.18	53.64	36
9	F	20	165.10	62.27	36
10	F	23	170	65.91	37
Average	--------	21.9	169.15	70.23	37.13
SD	--------	1.60	7.68	13.36	1.13

3.2.2. Experimental Set-up

The experiment was conducted in the Lifespan PsychoMotor Behaviour (LPMB) laboratory at Wilfrid Laurier University. The experimental design was set up in a large rectangular room (14 m by 6 m) with a 10 m pathway cleared along the midline of the room. A small visible goal was located at the end of the pathway in line with the participant's starting position. A space (7 m by 2 m) resembling the confinement of a sidewalk was outlined on the ground using yellow duct-tape. The participant and confederate were instructed to not walk outside this space (Figure 1a).

Kinematic data was collected using the Optotrak motion analysis system (Northern Digital Inc., Waterloo, ON) at a sampling frequency of 60 Hz. To monitor the position of each participant in space and with respect to the confederate throughout the experiment, both the participant and confederate were outfitted with a rigid body containing three Infrared Emitting Diodes (IREDs). Each participant was outfitted with a front-facing rigid body marker set-up, whereas the confederate was outfitted with a rear-facing marker set-up (Figure 1b). The markers were mounted to the participant and confederate using a harness to ensure the markers remained secured on the sternum of the participant and the 10^{th} thoracic vertebrae of the confederate. In addition to the rigid bodies, points were digitized on the participant's left and right glenohumeral (GH) joint and left and right anterior superior iliac spine (ASIS), as well as the confederate's left and right glenohumeral (GH) joint and left and right posterior superior iliac spine (PSIS).

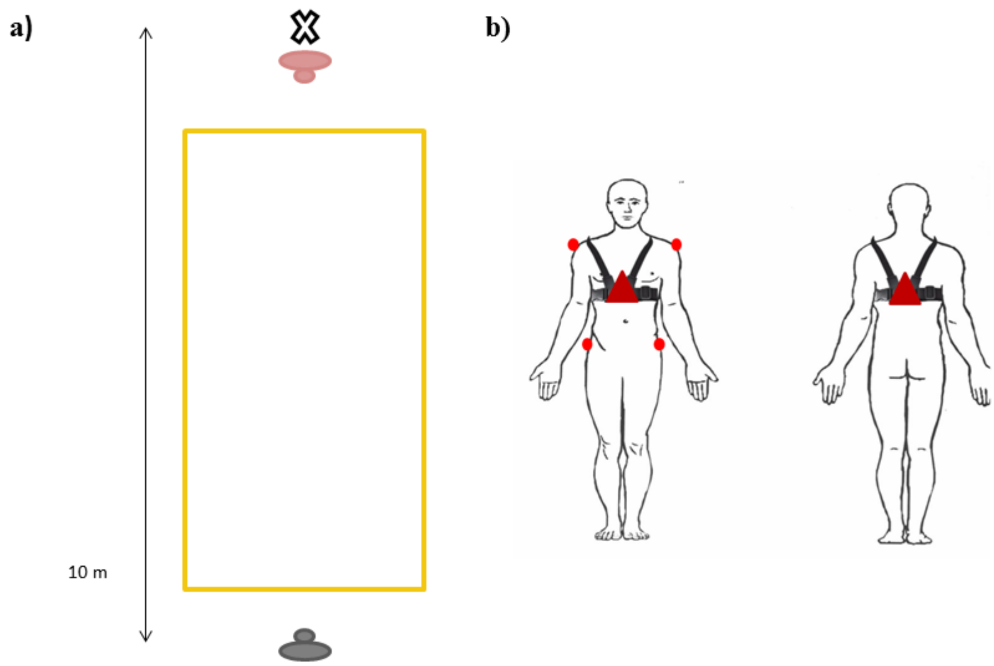

Figure 1a) Experimental space including a 2m x 7m space outlined in yellow duct tape. Participants were instructed not to leave this area to more realistically simulate a side walk. A visible goal (X) was located along the midline 10 m from the participant. The participant and confederate began each trial along the midline of the path, 180˚ from one another.
b) Experimental Marker set-up, including participant (left) and confederate (right).

3.2.3. Procedure

Prior to the start of the experiment, each participant completed 5 baseline walking trials. These trials consisted of the participant walking straight from her start position to the aforementioned goal. For all other experimental trials, the confederate stood facing the participant; 10m away from the participant's starting location, just in front of the participant's goal. The participants were instructed to walk at their normal pace towards the goal without colliding with the approaching person (i.e., confederate). More specifically, the participants were assigned the role of "the avoider" in which they had to avoid colliding with the confederate, "the avoided". However, no explicit instructions were provided as to how to avoid the confederate.

The participant and confederate began moving simultaneously. At 2.5 m from her starting location, the confederate would walk towards one of four predetermined positions: 1) 1m to the left of the participant's starting position; 2) along the midline of the pathway in-line with the participant's starting position; 3) 1m to the right of the participant's starting position; or 4) stopped along the midline 2.5 m from her start position. Participants completed 10 trials of each condition, presented in a random order, for a total of 40 experimental trials. Breaks were permitted as desired between trials. Following the experiment, a debrief was conducted with each participant in order to explain the role of the confederate and the necessity of secrecy with respect to her role.

3.2.4. Data Analysis

The anterior-posterior (AP) and medial-lateral (ML) location of both the participants' COM and confederate's COM were calculated using a weighted average of the ML and AP coordinates of the digitized points (i.e., 0.25*left shoulder + 0.25*right shoulder + 0.25*left ASIS/PSIS + 0.25*right ASIS/PSIS). This estimate allowed for the calculation of:

1. ML spatial requirement: absolute medial-lateral (ML) distance (cm) between the closest passing shoulders of the participant and confederate at time of passing each other.
2. Change in travel path (time of avoidance): the point in time from the start of a participant's steady state locomotion to when the participant's ML COM position fell and stayed outside 2 standard deviations of their starting position (i.e., midline of pathway). This variable was used in order to calculate the rate of ML avoidance, time to ML spatial requirement and theoretical time of collision.

3. Rate of ML avoidance: the speed (cm/s) at which the participants moved in the ML direction (from time of change in travel path to time of passing) to avoid the confederate.
4. Time to ML spatial requirement: the time (s) in which it took the participants to reach their ML position at time of passing. This value was calculated using the ML spatial requirement (cm) and rate of ML avoidance (cm/s). This time is calculated from the time of avoidance to time of crossing.

6. Time to Collision (TTC): the time (s) that remained before a theoretical collision would occur between the confederate and participant had they both continued to walk at their average speed. Speed of the confederate and the participant was calculated using an average of the instantaneous velocities across 100 frames during the approach phase up until time of avoidance. Approach phase was calculated once individuals reached steady state.

$$TTC = \frac{\text{distance between participant and confederate at time of avoidance}}{(speed\ of\ participant)+(speed\ of\ confederate)}.$$

The median value from the 10 trials of each of the four conditions was used to examine the above variables. The median value was used in order to provide a more representative value for each participant’s behaviour. Standard deviations from the mean of the median values discussed above were calculated to represent variability. In addition, in order to determine the participant’s consistency in avoidance behaviours, the variability (standard deviation) of the above outcome measures across the 10 trials of each condition was evaluated.

3.2.5. Statistical Analysis

In order to determine whether the confederate's travel path (4 paths) and/or the sport specific training (2 groups) of the participants had an effect on the outcome measures, a mixed repeated-measures ANOVA was conducted. This analysis was completed for all kinematic variables discussed above. Effect size was reported using partial eta squared. Additionally, a Tukey's HSD post-hoc analysis was completed to identify where the significant differences existed as a result of the confederate's travel paths.

3.3. Results

Throughout the experiment, no collisions occurred between the participants and the confederate. Results revealed the confederate walked 119.88 ± 7.47 cm/s throughout the experiment. The physical differences between the athletes and young adults were determined using an independent t-test. Results revealed there were no significant differences between the athletes' and non-athletes' height (p=.83), shoulder width (p=.11), or weight (p=.83) (Table 1). Furthermore, none of the repeated measures ANOVAs performed in this study revealed any significant interactions across any of the variables, therefore only the main effects from each ANOVA will be discussed further.

Figure 2 shows the average paths of the confederate during each of the conditions as well as the paths from each trial of a representative athlete and non-athletes for each of the confederate path conditions. These figures illustrate the location of change in travel path (time of avoidance) and ML spatial requirement for each condition at time of passing.

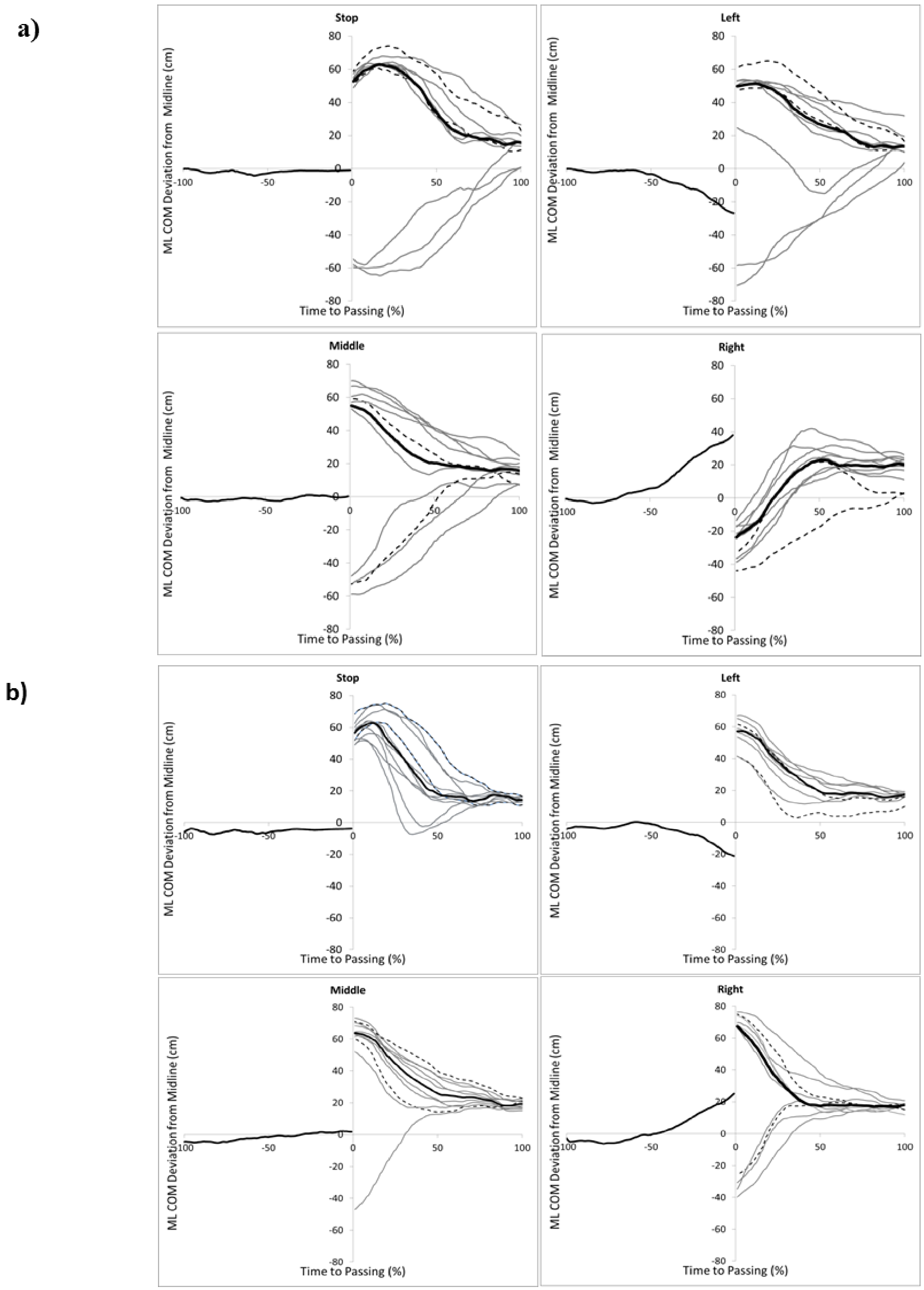

Figure 2: Paths of the confederate (black) and representative **a)** athlete and **b)** non-athlete participants across all path conditions. Figures displayed (from top left to bottom right) the stop, left, middle, and right confederate path conditions, respectively. Ten trials for each condition are depicted, the median of the condition is illustrated with the bolded line, and trials 1 and 10 are illustrated with dashed lines. Trials are illustrated as a percent of time to passing, such that 100% represents beginning of the trial and 0% represents time of passing.

3.3.1. Time to Contact (TTC)

TTC is the amount of time (temporal proximity) prior to colliding with an obstacle if the participant remains on the collision course. Cinelli and Patla (2007) observed that despite obstacle movement characteristics (i.e. approaching speed), the location of the participants' change in travel path occurred at the same location unrelated to the obstacle's temporal proximity. Therefore, individuals did not use a consistent TTC because although the approach speed of the obstacle was different, the path was highly predictable (Cinelli & Patla, 2007). Since the confederate's approach speed remained constant across all the conditions but the path was unpredictable, it was hypothesized that individuals would maintain a consistent TTC and change their path at a consistent temporal distance from the confederate. Although, a Mixed Repeated Measures ANOVA revealed a significant main effect of confederate path on TTC, $F_{(3,54)}=11.68$, $p<.0001$, $\eta^2=.393$. A Tukey's HSD post-hoc analysis determined participants avoided earlier when the confederate stopped 2.5 m from her starting position (1.54 ± 0.36 s) compared to travelling to the left of the participants (1.07 ± 0.46 s), along the middle of pathway (1.12 ± 0.54 s), and to the right of the participants (1.18 ± 0.47 s) ($p<.0001$, $p<.001$, and $p<.0001$, respectively) (Figure 3a). Additionally, Table 4 depicts the median and within-subject variability for each participant in the primary outcome, TTC.

Table 4: Within-subject variability for each confederate path condition for TTC.

Participant	$Stop_{Median}$	$Stop_{SD}$	$Left_{Median}$	$Left_{SD}$	$Middle_{Median}$	$Middle_{SD}$	$Right_{Median}$	$Right_{SD}$
Female Young Adults								
1	1.69	0.74	0.85	0.30	0.76	1.01	1.77	0.65
2	1.15	0.84	1.14	0.55	1.24	0.74	1.17	0.41
3	2.40	0.54	1.20	0.35	1.32	1.06	1.80	1.96
4	1.92	0.77	1.54	1.00	2.79	0.79	1.41	0.75
5	1.74	0.73	1.50	0.76	1.08	0.23	1.16	0.83
6	1.93	0.57	1.94	0.56	1.76	0.45	1.95	0.50
7	1.74	0.53	1.81	0.69	1.54	0.46	2.00	0.73
8	1.10	0.46	1.20	0.74	1.39	0.60	1.15	0.69
9	1.26	0.37	1.13	0.58	0.92	0.35	1.72	0.86
10	1.98	0.54	1.43	0.49	1.71	0.51	1.51	0.43
Female Athletes								
1	1.52	0.18	0.87	0.52	0.64	0.40	0.81	0.27
2	1.46	0.13	0.94	0.14	0.89	0.13	0.84	0.40
3	1.34	0.59	1.23	0.20	0.96	0.46	0.87	1.03
4	0.93	0.45	0.68	0.21	0.81	0.84	0.56	0.58
5	1.40	0.34	1.02	0.27	1.08	0.34	0.97	0.18
6	1.10	0.41	0.19	0.32	0.48	1.71	0.53	0.16
7	1.45	0.13	0.86	0.23	0.87	0.08	0.85	0.12
8	1.48	0.18	0.88	0.26	0.83	0.22	0.90	0.20
9	1.69	0.46	0.98	0.35	1.01	0.28	0.99	0.42
10	1.50	0.56	0.08	0.33	0.37	0.17	0.64	0.40

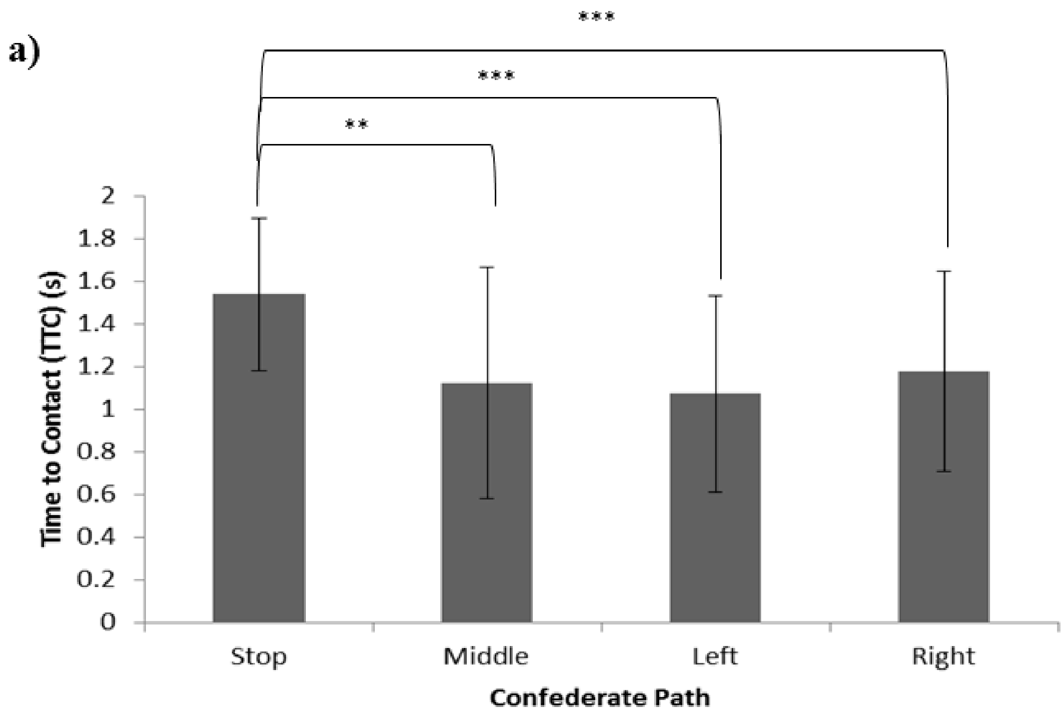

Figure 3: a) Time to contact (TTC) describes the temporal proximity prior to colliding with the approaching confederate when the participant initiated a change in path. This figure shows the average median TTC (seconds; with SD bars), which was significantly earlier when the confederate was stopped 2.5 m from her starting position compared to the all other pathways ($p<.001$, $p<.0001$, $p<.0001$, respectively)

In addition, Pfaff and Cinelli (2017) found that during sport specific contexts (i.e. running with a ball), rugby players elicited later avoidances than walking or walking with a ball (Pfaff & Cinelli, 2017). The current study presented a game-like scenario with the approaching obstacle being a human. As such, it was hypothesized that the athletes would initiate later avoidances compared to the non-athletes because they are trained to wait until an opponent is close to them before avoiding a collision. In line with the hypothesis, results revealed an effect of group (i.e., sport specific training) on TTC ($F_{(1,18)}=26.27$, $p<.001$, $\eta^2=.593$), such that athletes avoided significantly later (0.94 ± 0.30 s) than the non-athletes(1.52 ± 0.14 s) (Figure 3b).

Furthermore, it was hypothesized that athletes would be less variable in their avoidance behaviours than non-athletes. Results revealed a significant main effect of group ($F_{(1,18)}$=9.88, p<.05, η^2=.354), as such athletes were significantly less variable (±0.39 s) than non-athletes (±0.65 s)(Figure 3c).

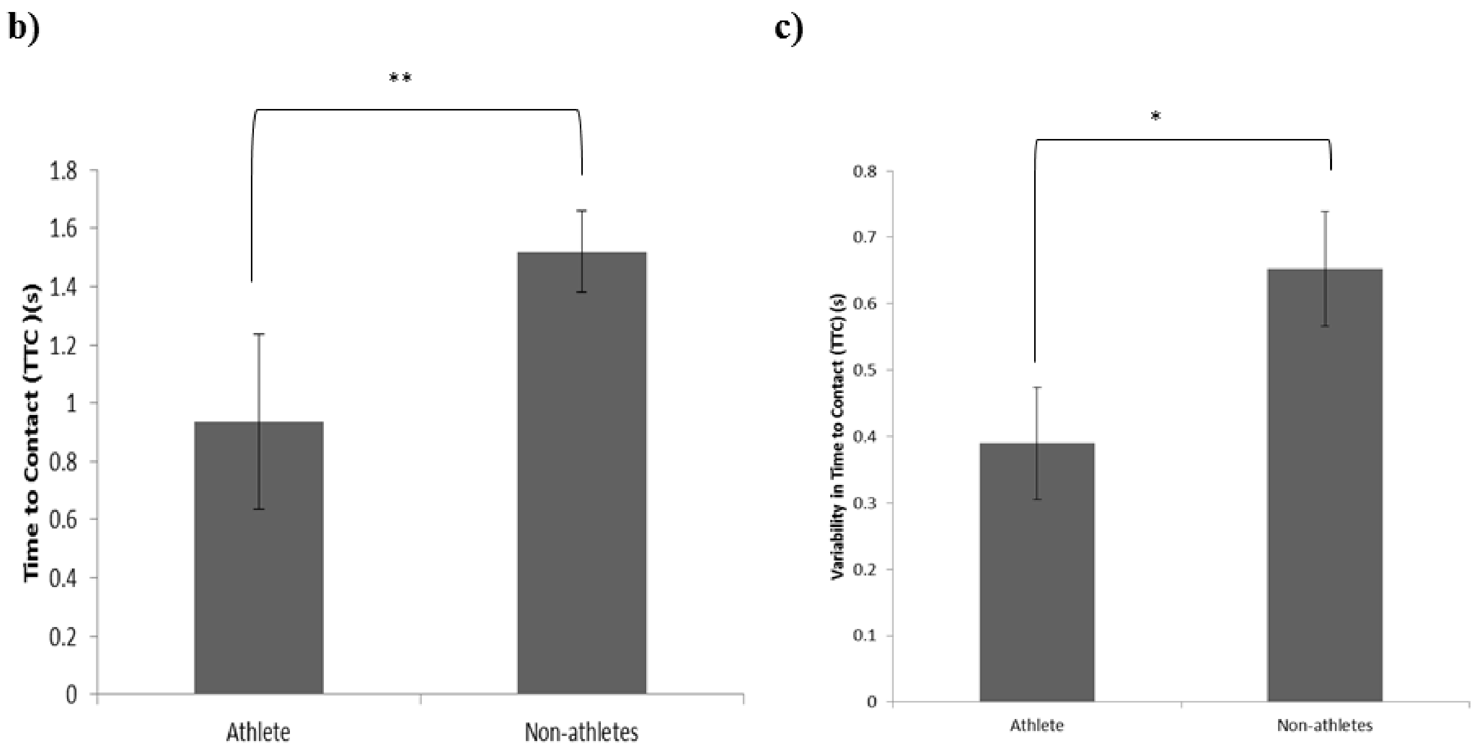

Figure 3: b) Non-athletes avoided significantly earlier than athletes (p<.001). **c)** Athletes were significantly less variable in TTC than non-athletes (p<.05)

3.3.2. ML Spatial Requirement

Possibilities for action are determined based on the fit between the environment, the individual's body size, and one's action capabilities (Fajen et al., 2008). More specifically, as suggested in the affordance-based model of obstacle avoidance, individuals consider their relative body dimensions during obstacle avoidance (Fajen, 2013). As such, it was hypothesized that ML spatial requirement would not be affected by the path of the confederate, but rather remain consistent across all path conditions. Although, contrary to the hypothesis, results suggested a main effect of confederate path ($F_{(1.804,32.469)}=22.78$, $p<.0001$, $\eta^2=.558$). A post-hoc analysis revealed that participants maintained a significantly greater ML spatial requirement when the confederate moved to the left of the participants (30.65 ± 8.0 cm) compared to when she stopped (19.57 ± 5.36 cm), walked along the middle of the path (18.41 ± 5.08 cm), and to the right of the participants (25.4 ± 9.29 cm) ($p<.0001$, $p<.0001$, and $p<.05$, respectively). In addition, ML spatial requirement was significantly greater when the confederate moved to the right of the participants than the middle of the pathway or stopped ($p<.01$) (Figure 4a).

Higuchi and colleagues (2011) found that football players, who are specifically trained to fit between small spaces, elicited significantly smaller and later shoulder rotations during an aperture crossing task than non-contact athletes while running (Higuchi et al., 2011). Therefore, it was hypothesized that the athletes would maintain a significantly smaller ML spatial requirement than the non-athletes. Contrary to the hypothesis, there was no significant difference between the ML spatial requirement of athletes (25.57 ± 7.37 cm) and non-athletes (21.44 ± 4.11 cm) ($p=.08$).

Additionally, Pfaff and Cinelli (2017) revealed that when athletes were moving in a sport specific context (i.e. walking or running with the ball), their ML spatial requirements were less variable than while moving without the ball (Pfaff & Cinelli, 2017). As the present study elicited a sport specific context with the use of an approaching confederate, it was hypothesized that athletes would be more consistent in their avoidance behaviours and exhibit less variability than their non-athlete counterparts. However, results revealed there was no significant difference in the variability in ML spatial requirement between the athletes (± 5.66 cm) and non-athletes (± 5.49 cm) (p=.86). Despite sport-specific training not having an effect on variability, results revealed a significant main effect of confederate path, $F_{(1.574,28.328)}=14.42$, $p<0.0001$, $\eta^2=.445$. A post-hoc analysis identified ML spatial requirement variability was significantly greater when the confederate moved to the right of the participants (±7.68 cm) compared to walking to the left of the participants (± 6.43 cm), along the middle of the path (±4.41 cm), and stopped 2.5 m from the start (± 3.79 cm) conditions (p<.05, p<.001, p<.0001, respectively). In addition, ML spatial requirement was significantly less variable during the stop condition than when the confederate moved to either extreme positions (i.e. left and right) (p<.01, p<.0001, respectively) (Figure 4b).

a) b)

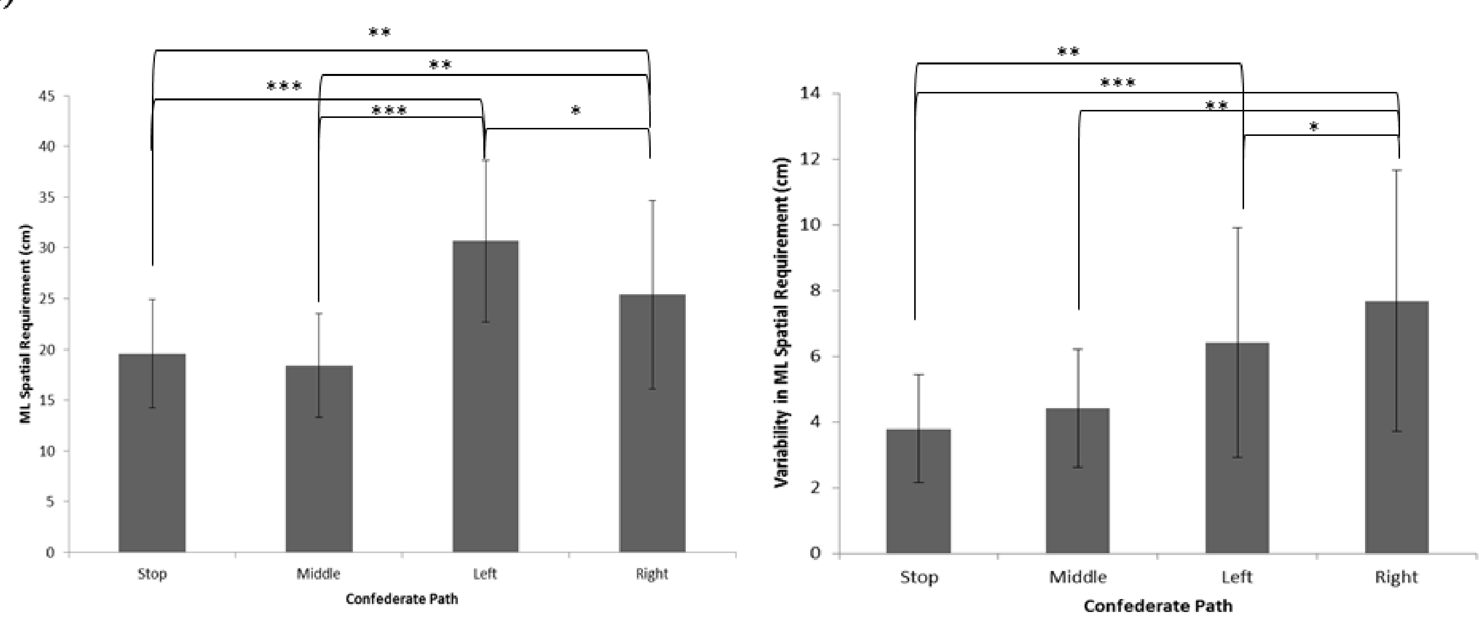

Figure 4: a) ML spatial requirement was the absolute ML distance between the participant's and confederate's closest shoulders at time of crossing. The figure shows the average median spatial requirement (centimetres; with SD bars), which was significantly larger when the confederate moved to the left compared to all other path conditions. **b)** Participants were more variable when the confederate moved to the right of the participant compared to all other path conditions.

3.3.3. Rate of ML Avoidance

When the confederate approached the participant along the midline, the participant and the confederate remained on a collision course until the participant initiated a change in path. Therefore, the greatest risk of collision existed during the middle condition. Since, TTC is assumed to be consistent across all path conditions, it was hypothesized that participants would avoid the confederate at a greater rate when the confederate approached along the midline in order to mitigate the risk of collision. Results revealed a significant main effect of confederate path on rate of ML avoidance ($F_{(1.415,26.113)}=20.86$, $p<.0001$, $\eta^2=.537$). A post hoc analysis identified participants avoided significantly faster when the confederate moved along the middle of the path (25.50 ± 10.42 cm/s) compared to when she stopped 2.5 m from her start (14.26 ± 5.79 cm/s) and walked to the left of the participants (18.27 ± 7.73 cm/s) (p<.0001) . However, there was no significant difference between the rate ML of avoidance between the conditions in which the confederate walked along the middle of the path and when she walked to the right of the participants (30.67 ± 12.28 cm/s) (p=.15). Additionally, participants avoided significantly slower when the confederate stopped 2.5 m from her starting position compared to all other path conditions (p<.0001)(Figure 5a).

Since it was believed that the athletes would avoid the confederate significantly later than the non-athletes, they would have needed to avoid faster than their non-athlete counterparts in order to successfully avoid the approaching confederate. However, results revealed there were no significant differences in the rate of ML avoidance between the athletes (24.42 ± 11.41 cm/s) and non-athletes (19.93 ± 3.37) (p=.105) (Figure 5b).

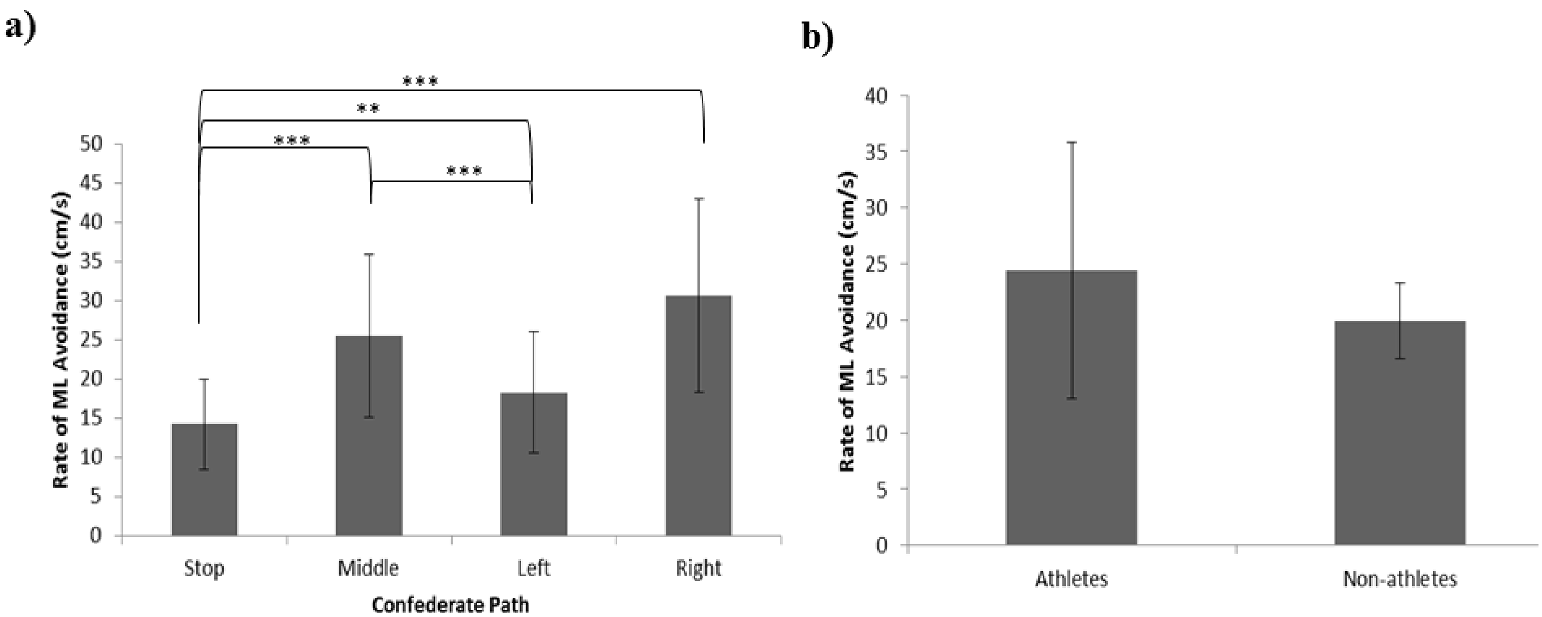

Figure 5: a) ML rate of avoidance describes the speed at which participants moved in the ML direction to avoid the confederate. The figures shows the average median speed (centimetres/second; with SD bars), which was fastest when the confederate walked along the midline compared to left and stop path conditions (p<.0001). Additionally, participants avoided slower when the confederate stopped compared to all other path conditions (p<.0001) **b)** Rate of ML avoidance was not significantly different across rugby players and non-athletes (p<.105).

Additionally, it was hypothesized that the rugby players would have a less variable rate of ML avoidance. Results revealed there was no significant difference in the variability in rate of ML avoidance between the athletes (± 9.11 cm/s) and non-athletes (± 8.28 cm) (p=.33). Although sport-specific training did not have an impact on variability in rate of ML avoidance, results revealed a significant main effect of confederate path ($F_{(3, 54)}$=4.07, p<.01, η^2=.184), such that participants were significantly less variable in the rate of ML avoidance when they avoided the stopped confederate (± 7.09 cm/s) compared when the confederate walked along the midline (± 10.18 cm/s) and to the right (± 9.17 cm/s) (p<. 001 and p<.05, respectively).

3.3.4. Time to ML Spatial Requirement

In order to observe the temporal control of the individuals' avoidance behaviours, the time to reach their ML spatial requirement was calculated. Results revealed a significant main effect of confederate path ($F_{(1.664, 29.945)}$=10.67, p<.001, η^2=.372). A post hoc analysis identified, participants took more time to avoid when the confederate was stopped (1.71 ± 1.10 s) then when the confederate walked down the middle (0.93 ± 0.36 s) or to the right (0.89 ± 0.68 s) (p<.0001 and p<.005, respectively). Additionally, participants took more time to avoid when the confederate walked to the left (2.27 ± 1.83 s) than the middle (p<.001) and right (p<0.005) (Figure 6). Furthermore, there were no significant differences in the time it took the athletes (1.75 ± 1.02 s) and non-athletes (1.16 ± 0.34 s) to reach their ML spatial requirements (p=.13).

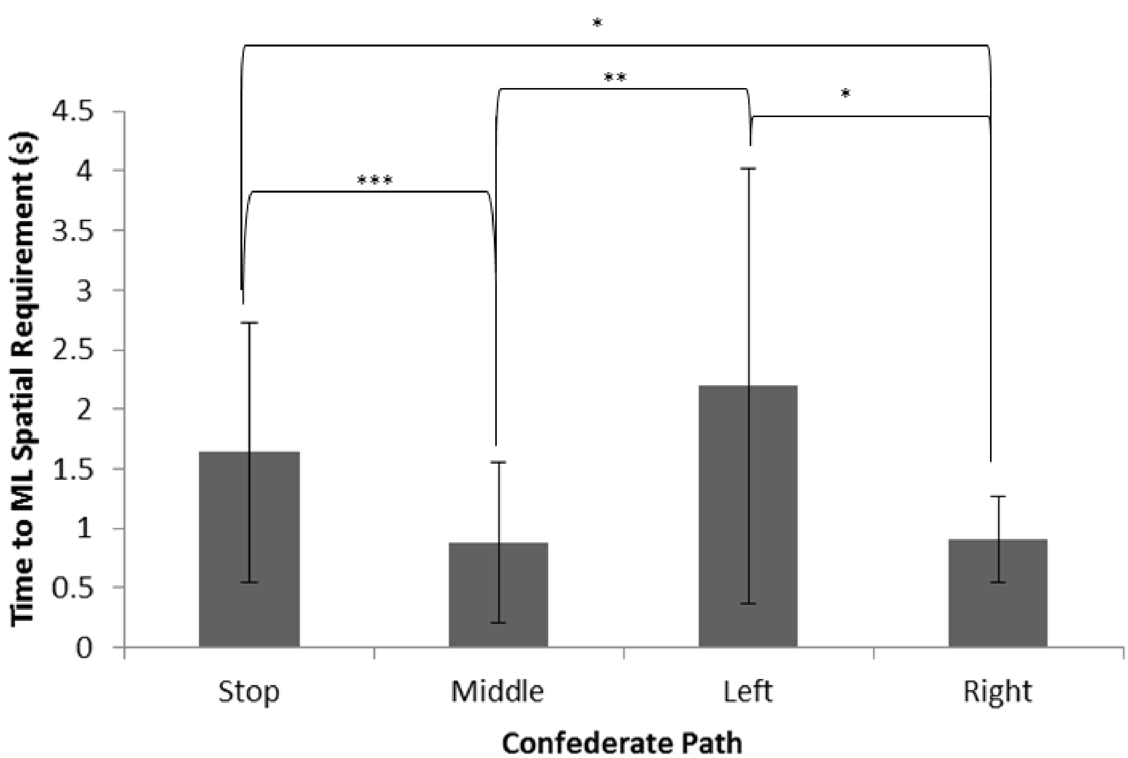

Figure 6: Time to ML spatial requirement depicts the time it took the participant to reach their ML spatial requirement at time of crossing. The figures shows the average median time (seconds; with SD bars), which was slowest when the confederate stopped compared to when the confederate walked down the middle (p<.0001) or right (p<.005). Additionally, the confederate took more time to avoid when the confederate moved to the left than the middle (p<.001) and right (p<.005).

3.4 Discussion

The current study set out to identify the effects of sport-specific training on avoidance strategies during a head-on collision course with an approaching person. The current study found individuals, regardless of training, maintain a relatively similar elliptical shaped protective zone (Figure 7) (Gérin-Lajoie et al., 2008; Hackney et al., 2013). This protective zone is made up of both temporal and spatial components. The time at which individuals changed their path (i.e. AP temporal requirements) can be thought of as the driving factor in "when" an individual avoids, and the following avoidance strategies, including ML spatial requirement, rate of ML avoidance, and time to ML spatial requirement, may be considered "how" an individual avoids.

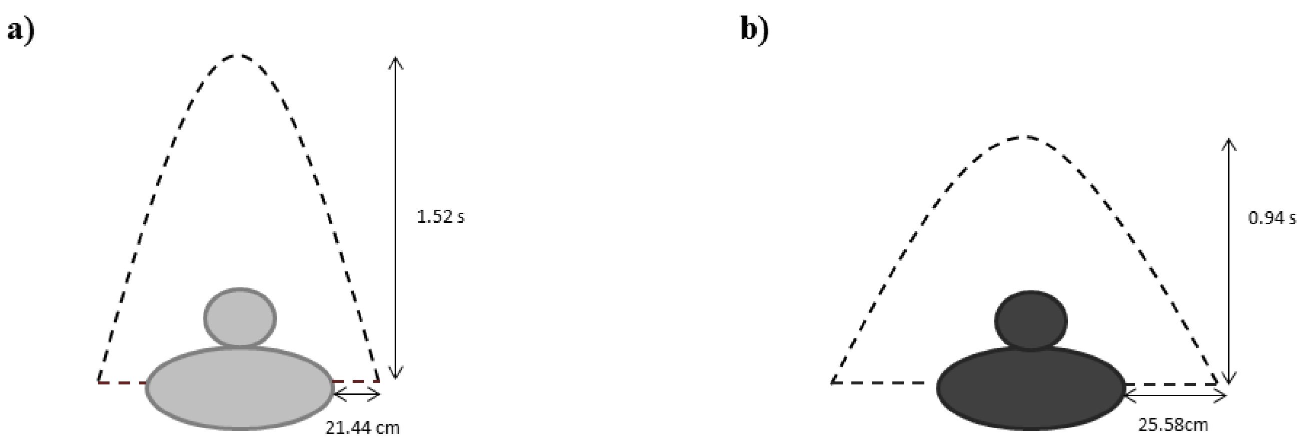

Figure 7: Average personal space boundaries maintained by a)non-athlete and b) athlete participants across all confederate path conditions. Non-athletes maintained a significantly greater temporal space between themselves and the confederate compared to athletes ($p<0.001$).

3.4.1. Time to Contact (TTC) ("When")

Determining when to initiate an avoidance behaviour is dependent on visual information. The ability to determine the temporal proximity prior to contacting an object, known as TTC, is vital in initiating avoidance behaviours. In contrast to Cinelli & Patla (2007), the path of the approaching obstacle (i.e. confederate) was highly unpredictable; therefore, it was hypothesized that individuals would use a consistent TTC to initiate a change in path. Findings revealed individuals avoided earlier when the confederate stopped 2.5 m from her starting position compared to all other path conditions (Figure 3a). When the confederate stopped, there was less uncertainty in her movements and therefore individuals may have required less visual information in order to determine when to change their path. This finding is in line with previous research which suggests individuals maintain a greater personal space when approaching a stationary obstacle compared to a moving obstacle (Gérin-Lajoie et al., 2005).

Rugby players have been found to initiate avoidance behaviours later during a sport specific context (Pfaff & Cinelli, 2017), therefore it was hypothesized that the athletes would avoid later compared to the non-athletes. The current study confirmed that athletes did initiate an avoidance significantly later than non-athletes (Figure 3b). This behaviour suggests athletes with specific training may better perceive their action capabilities and in turn have better perception for action skills (Fajen et al., 2008). By initiating a later avoidance, athletes may protect their movement decisions from opposing players in order to gain an advantage on the field. By successfully perceiving their action capabilities, they may avoid later than their non-trained counterparts and still successfully avoid collision. Although, previous literature has found athletes do not differ from non-athletes in their AP spatial requirement (Baker, 2015; Hackney, Zakoor, & Cinelli, 2015), the temporal measure of TTC may tease out otherwise unnoticeable differences in their avoidance strategies.

The athletes were also found to be less variable in their TTC than the non-athletes (Figure 3c), suggesting the rugby players were able to use the visual information from the environment more successfully. Previous research suggests athletes have longer fixations than non-athletes (Baker, 2015); as such, they may use a more effective visual sampling to obtain more salient information from the environment in order to make more consistent avoidance behaviours.

3.4.2. Avoidance strategies ("How")

After an individual has determined when to initiate an avoidance, how they will avoid the obstacle is also critical in their success. Originally, it was hypothesized that ML spatial requirement would be regulated by the individual and her previous training as opposed to the path of the confederate. However, results from the current study found that individuals maintained a greater ML spatial requirement when the confederate moved to either extreme position (left or right) compared to stopping or walking along the midline (Figure 4a). Individuals may have been less constrained by the environment (i.e. yellow duct tape identifying ML limits) when the confederate moved to either side compared to when the confederate walked along the midline. When the confederate moved to either the left or the right it was easier for the participants to identify and move to the opposite side of the path because there was more open space than when she walked along the midline which decreased the space available on either side (Gibson, 1979). Therefore, when the confederate moved to either extreme, the environment allowed the participants to select the path which afforded a greater ML spatial requirement.

Regardless of the path selection of the confederate, it was hypothesized that the rugby players would maintain a smaller and less variable ML spatial requirement at the time of passage. The current study found that the ML spatial requirement was not significantly different between athletes and non-athletes. This finding is supported by previous literature which did not observe significant differences in ML spatial requirements during aperture crossing between athletes and non-athletes during both walking and running, respectively (Baker, 2015; Hackney, Zakoor, et al., 2015). However, Higuchi and colleagues (2011) were able to demonstrate that football players maintained smaller ML spatial requirements while running through apertures compared to non-contact athletes. The primary difference between the current study and that of Higuchi and colleagues (2011) is the latter forced athletes through the aperture, whereas the current study allowed participants to choose their own paths. The current study suggests that the spatial requirement necessary for safe passage when avoiding an obstacle 180^{o} to one's path may be driven by body-scaled information (shoulder width) as opposed to action-scaled because all individuals maintained relatively the same ML spatial requirement at the time of passage.

The variability in ML spatial requirement was also not significantly different across athletes and non-athletes (Figure 4b). The lack of difference in variability between athletes and non-athletes suggests the present study may not have provided the athletes a context that was sport-specific enough to tease out the effects of training. However, the path of the confederate impacted variability in ML spatial requirement, such that it was greater when the confederate moved to the right compared to all other path conditions. Participants may have been more variable in the ML spatial requirement when required to avoid to the left of the confederate, because North American norms typically encourage rightward passage (sidewalk and driving).

The instructions provided during the experiment specified that the participant was required to initiate all avoidances in order to not collide with the approaching confederate (i.e. “avoider” vs “avoided” roles). Therefore, when the confederate walked along the midline of the pathway, it provided the greatest risk of collision if the participant did not change their path. As such, it was hypothesized that participants would avoid at a significantly faster rate when the confederate walked along the midline to reduce the threat of collision. The current study found that participants did in fact avoid the confederate at the fastest rate when she walked along the midline compared to the left and stop conditions (Figure 5a). This finding is consistent with that of Cinelli and Patla (2007), who observed, as the threat for collision increases (i.e. increased approaching velocity), individuals will avoid the obstacle at a faster rate.

Since the athletes avoided significantly later than the non-athletes (i.e., lower TTC), it was expected that in order to reach the same ML spatial requirement they would also have to avoid at a faster rate. However, results revealed athletes did not avoid the confederate at a faster rate than non-athletes. Although the average rate of avoidance was not different between athletes and non-athletes, when examining the raw paths of the representative athlete compared to the representative non-athletes (Figure 2), it may be observed that the instantaneous rates rather than overall rates may differ across the avoidance. Therefore, the time at which the athletes avoided faster (i.e. beginning of avoidance) may differ from their non-athlete counterparts.

In order to identify whether individuals are controlling spatial or temporal components of the avoidance, the time to ML spatial requirement was calculated. It was found that the time to ML spatial requirement was driven by the path of the confederate. More specifically, individuals took more time to avoid when the confederate was stopped or walked to the left of the participant compared to the middle or right paths. In line with the ML spatial requirements finding, individuals may be more comfortable when avoiding a stationary obstacle (i.e. stop condition) and along the right, and therefore did not feel as though they needed to rush. Alternatively, individuals may have taken more time during their avoidance when the confederate was stopped as a result of experimental design. The participants may have taken longer to reach their ML spatial requirement due to the fact that the confederate was stopped further from them at time of avoidance.

Overall, it was found that variability in the avoidance strategies (ML spatial requirement and rate of ML avoidace) was not impacted by sport-specific training, but rather the path of the confederate. This may have occurred because, although athletes are highly trained in obstacle avoidance, it is the end outcome that drives their behaviour rather than the specifics in how they reach that outcome. This idea is supported by the theory of optimal feedback control, which states variance is only reduced in variables that are relevant to the task outcome (Todorov & Jordan, 2002).

3.5 Conclusion

The present study found that avoidance strategies are impacted by changes to the environment and the observer. Rugby players and non-athletes used online control to guide their avoidance behaviours throughout the experiment. Training may impact when an individual avoids an approaching obstacle, such that, athletes may be using more fine-tuned visual information and their action capabilities to determine when to initiate an avoidance (i.e. TTC). The manner in which an individual avoids an approaching person is not be dependent on training (action capabilities), but rather the environment (path selection of the confederate). The current study illustrated that individuals are not consistently controlling their avoidance strategies across environments. More specifically, avoidance behaviours including ML spatial requirements, rate of avoidance, and time to ML spatial requirement, were not consistent across training or path conditions.

Chapter 4

General Conclusions

The objective of the present thesis was two-fold. First, it set out to examine the avoidance strategies of young adults during a head-on collision course with an approaching person. Additionally, the effects of sport-specific training on avoidance strategies during a collision course were investigated. The ability to successfully avoid an approaching person is critical in safely moving through an everyday, dynamically changing environment. The ability to do so in a sport setting presents more dire consequences if unsuccessful. The results from these two studies show that individuals use visual information in order to guide their avoidance behaviours, however the magnitude and level of control differ across individuals and environment.

When the pathway of the approaching confederate was unknown (which is typical of everyday life), individuals used a consistent TTC in order to determine when to change their path. The use of TTC may be impacted by characteristics of the observer. More specifically, males avoided earlier than females. These differences may emerge as the result of individuals' using body-scaled information in addition to the optical expansion threshold to guide their avoidances. Additionally, athletes avoided significantly later and showed greater consistency in their use of TTC than non-athletes. Athletes who are specifically trained to fit between spaces and avoid obstacles may consider their action capabilities in conjunction with their visual information to determine time of avoidance. These findings add to the understanding of the effects of sport-specific training on the way in which athletes use their visual information when determining avoidance behaviours. Future research should assess these behaviours in a more context-specific environment.

When examining the behaviours following a change in pathway, the two studies suggest avoidance behaviours are not impacted by sport-specific training or sex, but rather individuals use online control to guide their avoidance strategies. Neither males, females, non-athletes, nor rugby players displayed a significantly different navigational strategy during this experiment. It is clear that individuals employed a number of solutions dependent on the environment and task constraints in order to successfully avoid the approaching confederate. When the path of the confederate was uncertain, individuals did not use a single avoidance strategy, but rather considered the fit between their individual characteristics (i.e., body size and action capabilities) and components of the environment (i.e. path of the confederate and task constraints). Since it is known that perception and action are dependent on one another, future research should aim to collect gaze data to assess what information individuals are using to guide their actions.

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Appendix A

Health History Questionnaire

We are interested in your personal history because it may help us to better understand the results of our study. Your answers to a few short questions will aid us in this effort. All answers will be kept strictly confidential. You may choose not to provide a response to any questions without penalty.

Demographics:

1. Age:___________

2. Year of Birth: ________ Month of Birth: _________

3. Height: _______________

4. Weight: _______________

5. Gender:_______________ [4]

6. Current Employment:_____________________________

Vision:

7. A) Do you have:

Glaucoma . . . .NO / YES
Cataract(s) . . . . ….NO / YES
Macular degeneration . . . .…NO / YES
Amblyopia/ Lazy Eye/ Binocular vision defect (i.e. turned down eye) ..NO / YES

B) Have you ever had eye surgery for:

Glaucoma . . . . .NO / RIGHT / LEFT Date:________________
Cataract(s) . . . . .NO / RIGHT / LEFT Date:________________
Macular degeneration . . . .NO / RIGHT / LEFT Date:________________
Corneal/lens transplants . . NO / RIGHT / LEFT Date:________________
Laser eye surgery . . . . NO / RIGHT / LEFT Date:________________

C) Do you currently receive medical treatment for your eyes? . . . . NO / YES
If **YES**, what kind? ____
Patching/ Vision Therapy?____

D) Have you ever seen a doctor for an eye injury? . . . . NO / YES
Describe: ____

8. Have you ever been unconscious, had a head injury or had blackouts?
A) NO / YES
B) Cause:____
C) Duration:____

D) Treatment:____
E) Outcome:____
F) Year(s): ____

9. Have you been seriously ill or hospitalized in the past 6 months?
   A) NO / YES
   B) Cause:____
   C) Duration:____

Do you have now, or have you had in the past :

10. a) A Stroke? b) Transient ischemic attack?	NO / YES NO / YES	When?
11. Heart disease?	NO / YES	Nature (MI, angina, narrowing of arteries):
12. High blood pressure?	NO / YES	Is it controlled?
13. Seizures?	NO / YES	Age Onset:______ Frequency:____________ Cause:___________ Treatment:____________
14. Epilepsy?	NO / YES	
15. Frequent headaches?	NO / YES	Tension / migraine
16. Dizziness?	NO / YES	
17. Trouble walking? Unsteadiness	NO / YES	
18. Arthritis?	NO / YES	
19. Any injuries to the lower limb? (e.g. hip, knee, ankle)	NO / YES	
20. Serious illness (e.g. liver disease)?	NO / YES	
21. Neurological disorders?	NO / YES	
22. Anxiety?	NO / YES	
23. (Other) psychological difficulties?	NO / YES	

24. Medication: Please list the medication you are currently taking and any other medication that you have taken in the past year

Type of medication	Reason for consumption	Duration of consumption and Dose

25. Present Problems - Are you currently troubled by any of the following?

Concentration/ Attention problems	NO / YES	Nature:
Memory problems	NO / YES	Nature:
Difficulties finding words	NO / YES	Nature:

26. Physical Activity

How many times per week do you take part in physical activity (e.g., walking, gardening, household chores, dancing) or exercise? ________

Please list the types of physical activities that you partake in:

Activity	**Number of times per week**